Ushering in DES Cluster Cosmology with redMaPPer

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1: Why Should You Care About Clusters?

The Big Picture

An accelerating Universe requires one of two possibilities to be true:

- The energy budget of the Universe is dominated by *dark energy* (possibly a cosmological constant)
- General Relativity (GR) is an incorrect theory of gravity on cosmological scales.

How can we distinguish between these two?

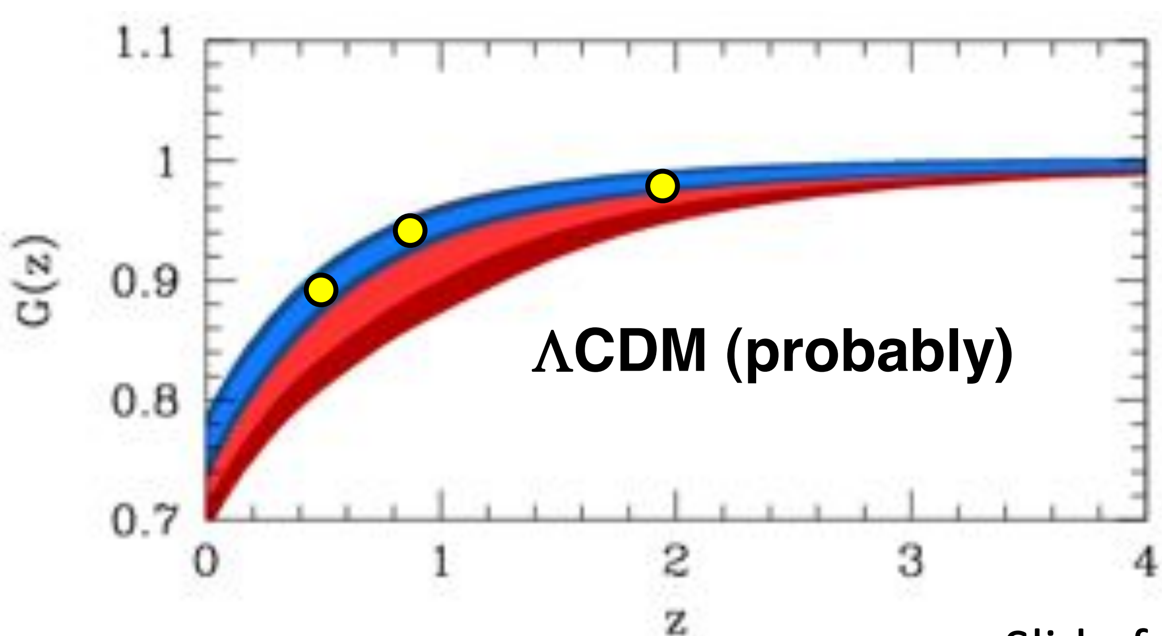
Testing GR with Dynamical Probes

1. Take initial conditions from CMB. (WMAP/Planck)
2. Measure expansion history. (BOSS)
3. Use GR to predict growth of structure.
4. Compare with observed structure.

Galaxy clusters can provide step 4.

Why It's Interesting

Clusters can falsify DE+GR



ΛCDM

quintessence

(68 / 95% CL)

Slide from Mortonson

Cluster Cosmology

Galaxy clusters are the most massive gravitationally bound structures in the Universe.

More structure = larger inhomogeneities

= more, bigger clusters.

No. of galaxy clusters as a function of mass measures the amount of structure in the Universe (σ_8).

Focus today on cluster detection.

2: Cluster Detection

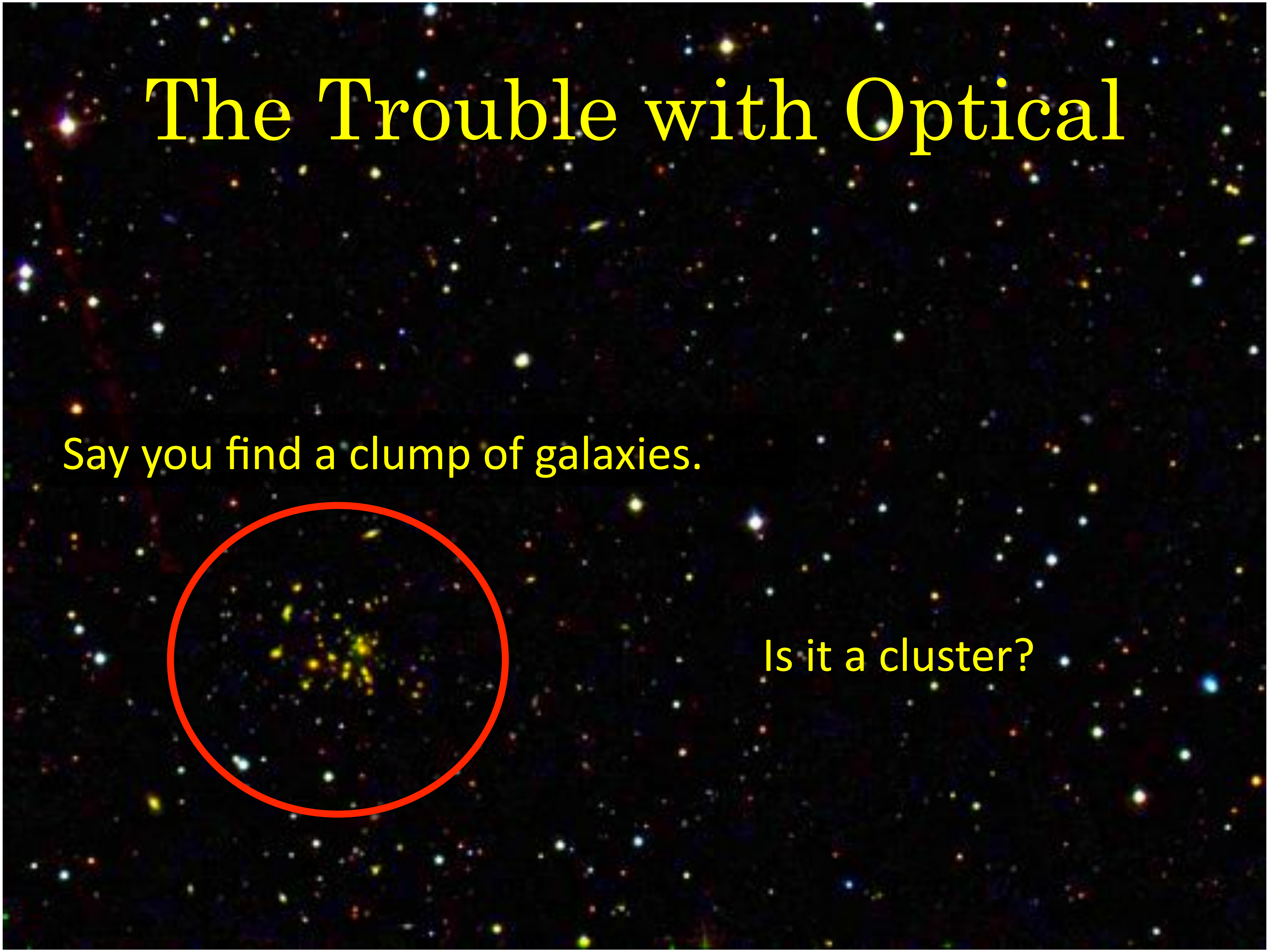
Several Methods

- X-rays: very good at finding clusters, but mass limit increases quickly with redshift.
- SZ: good for massive objects only (though this may change in ~3 years), nearly redshift independent.
- Optical good for low mass objects out to z~1 (DES) or z~1.5 (LSST).

X-ray/SZ need optical data for redshifts/WL masses.

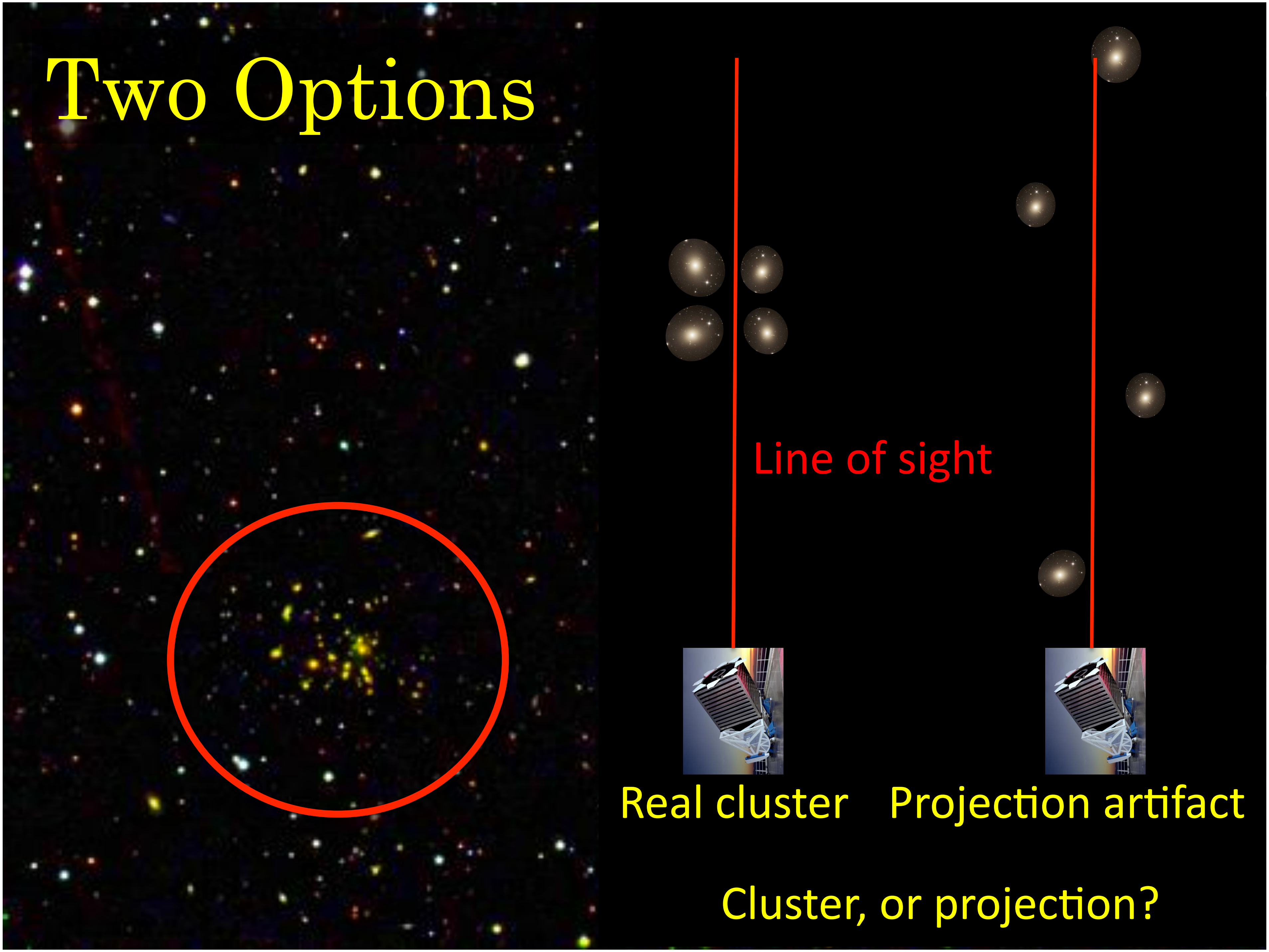
Results ultimately limited by optical coverage.

The Trouble with Optical

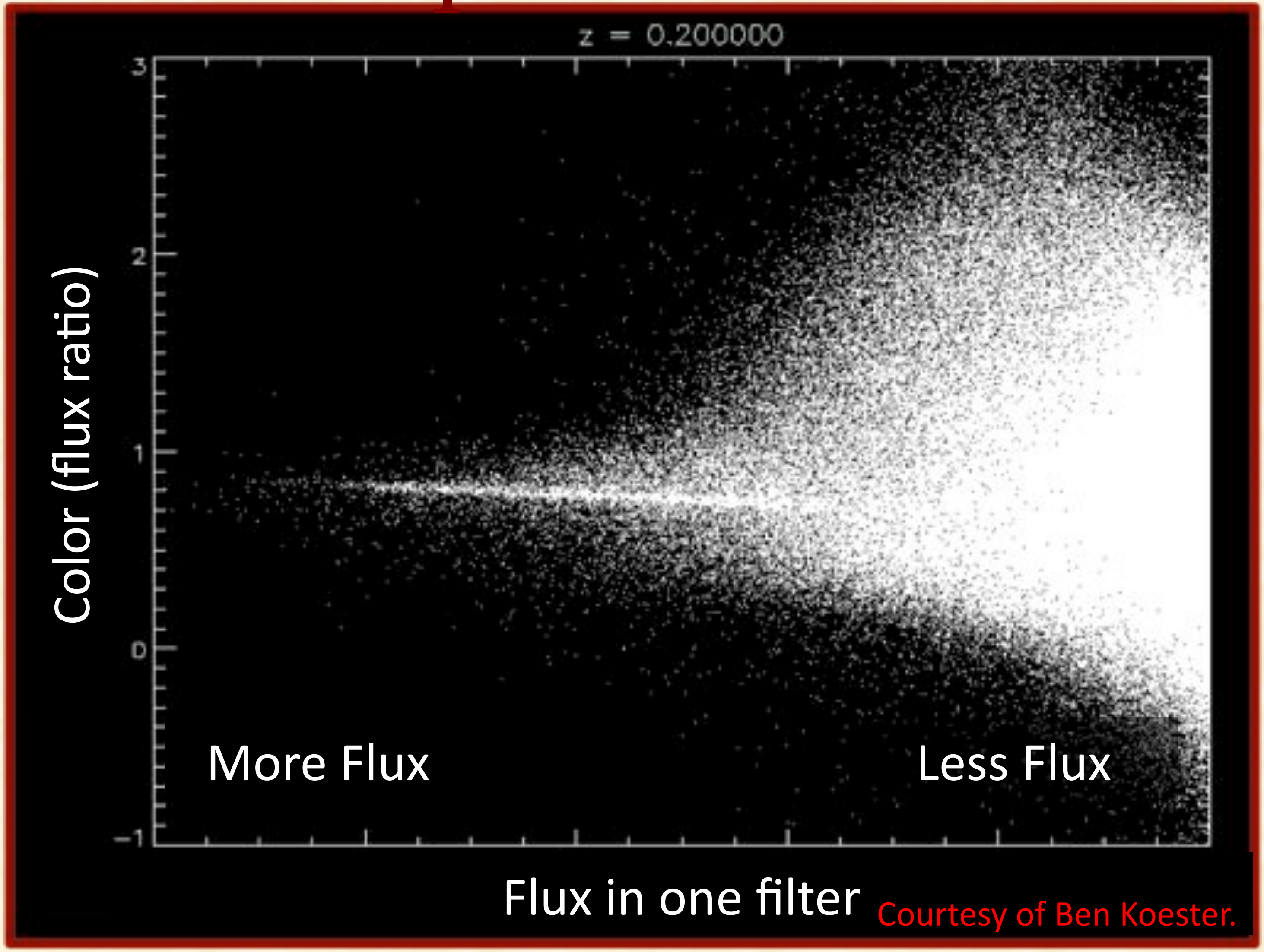


Say you find a clump of galaxies.

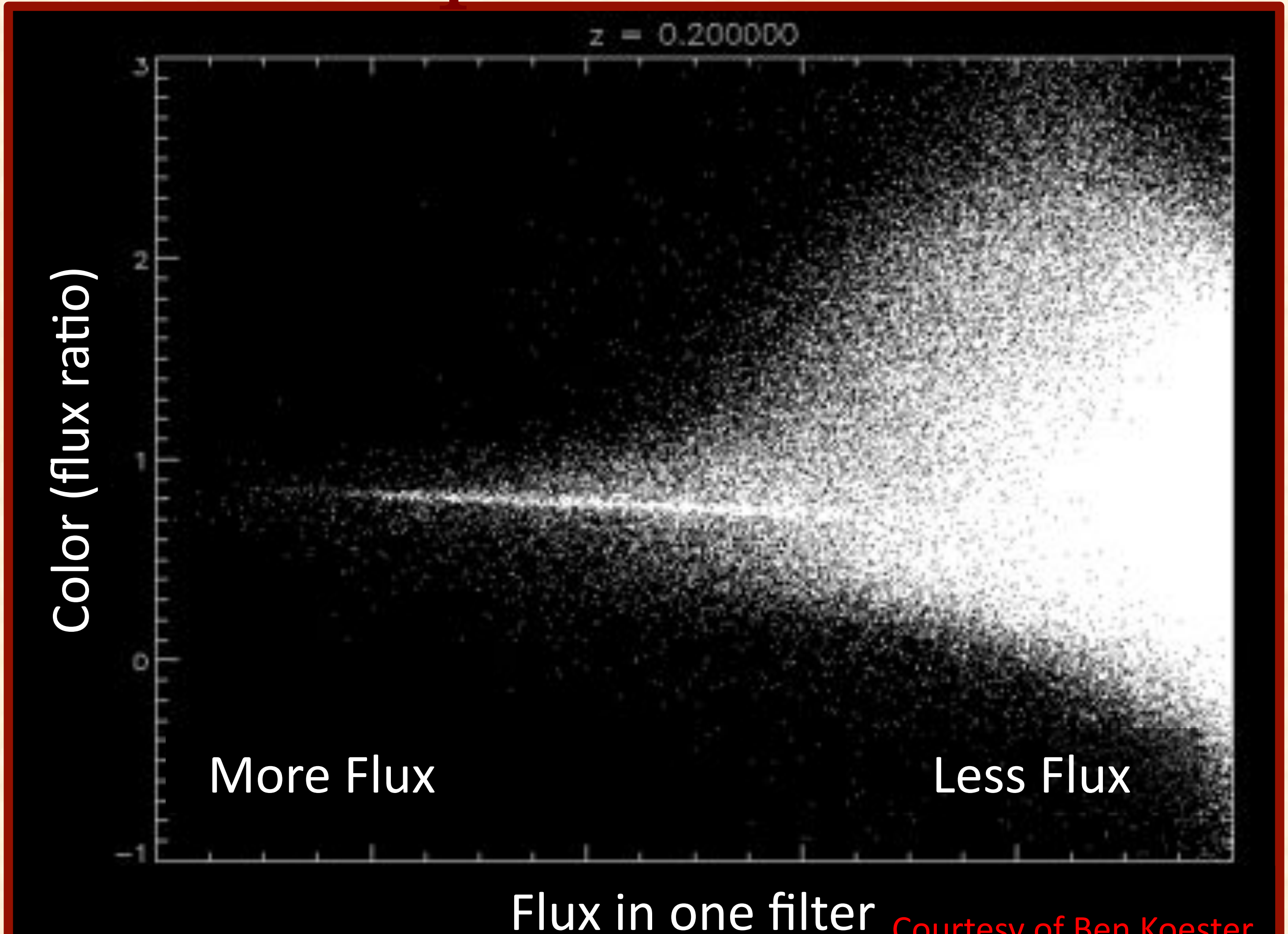
Is it a cluster?


Two Options
Line of sight
Real cluster
Projection artifact
Cluster, or projection?

Combating Projections: The Red-Sequence Method



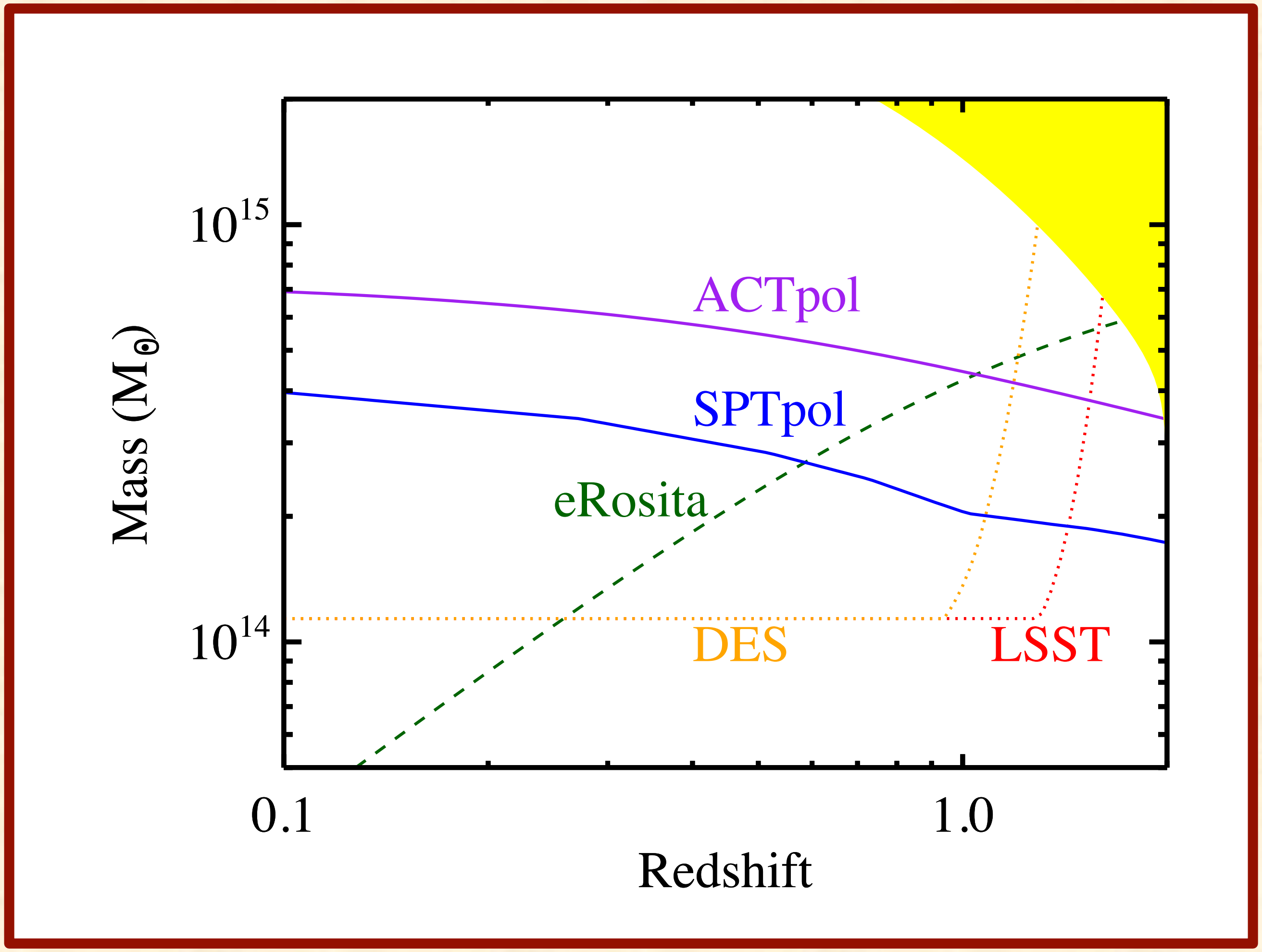
Combating Projections: The Red-Sequence Method



Courtesy of Ben Koester.

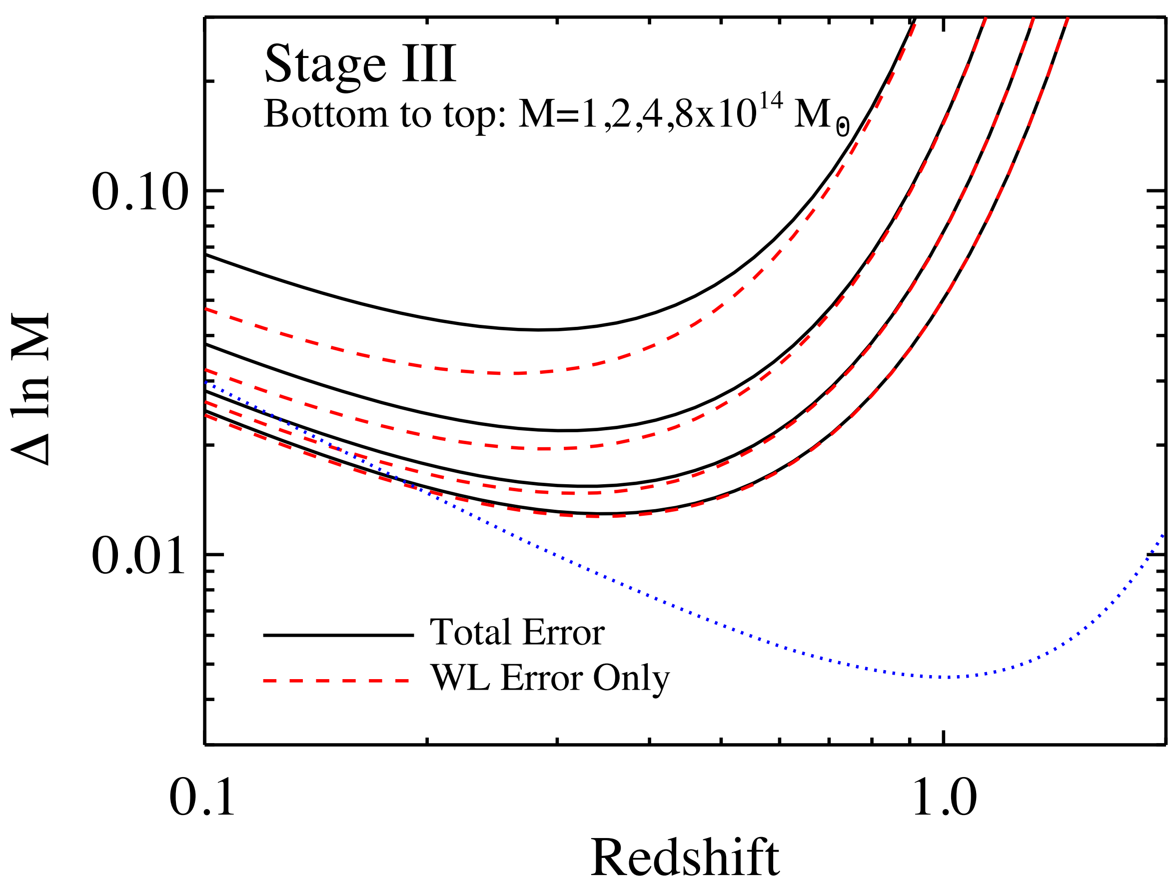
So Why Bother Detecting in the Optical?

Optical Allows Detection of the Low Mass Systems



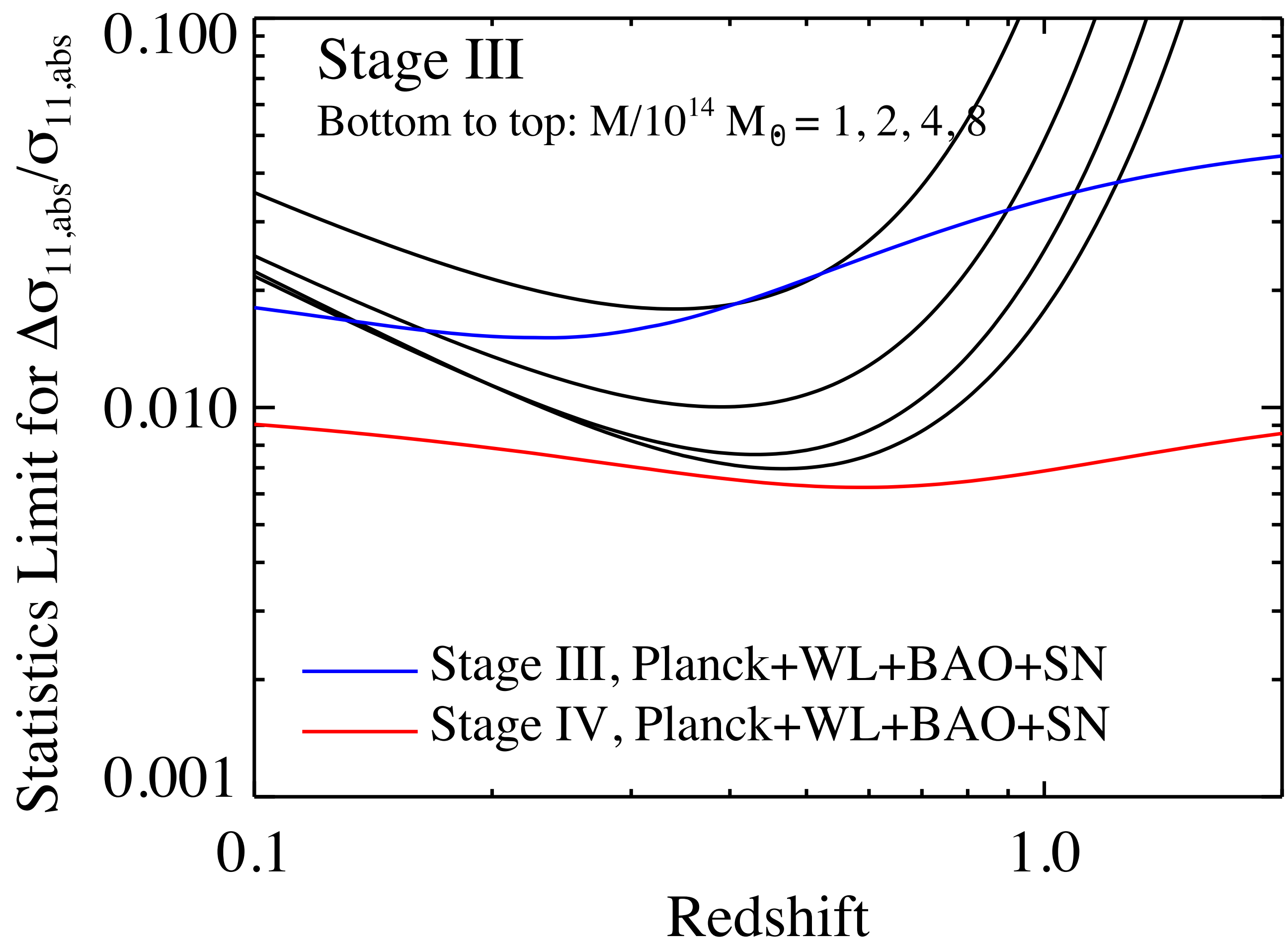
Weinberg et al. 2012

So?



low mass = more abundant = better WL masses!

Better Masses = Better Cosmology



Weinberg et al. 2012

Bottom Line

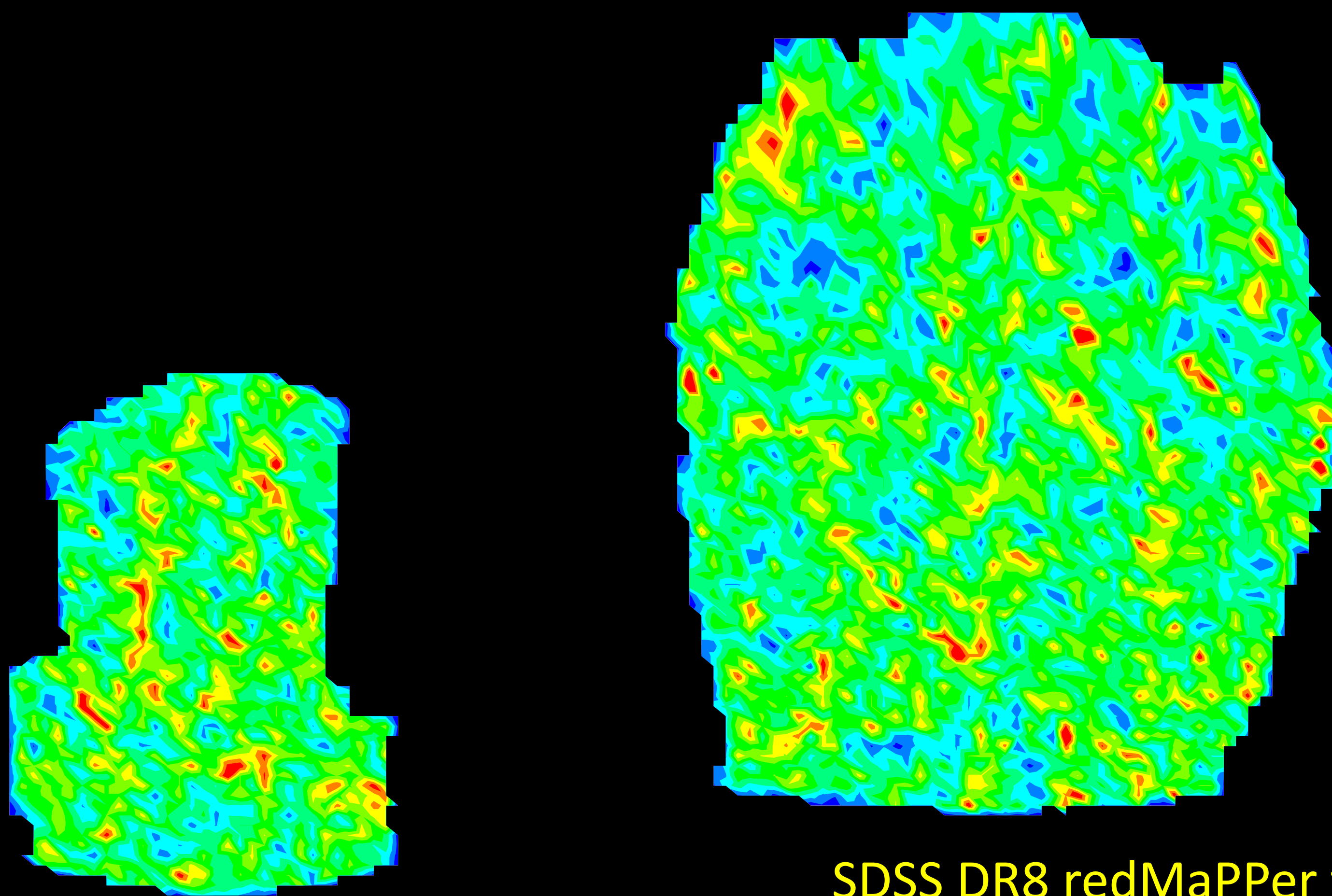
Finding clusters in the optical maximizes the cosmological information that can be drawn from clusters.

X-ray/SZ still play a critical role!

Optical detection has its own set of systematics, which can (should!) be calibrated with X-ray/SZ data.

Combination of data sets is clearly more powerful than any data set alone. (Wu et al. 2010, Cunha et al. 2010).

3: Detecting Clusters in the Optical: *redMaPPer*



SDSS DR8 redMaPPer footprint

Warning: Sales Pitch

redMaPPer

Red-sequence Matched-Filter Probabilistic Percolation

• New cluster finding algorithm.

• Specifically optimized for large, multi-band photometric surveys (e.g. DES, LSST)

Key feature: self-trains red-sequence model.

redMaPPer: Self-Training

Start with *spectroscopic galaxies* (seeds).

Use photometry to look for clusters around seed galaxies using initial simple model for red-sequence.

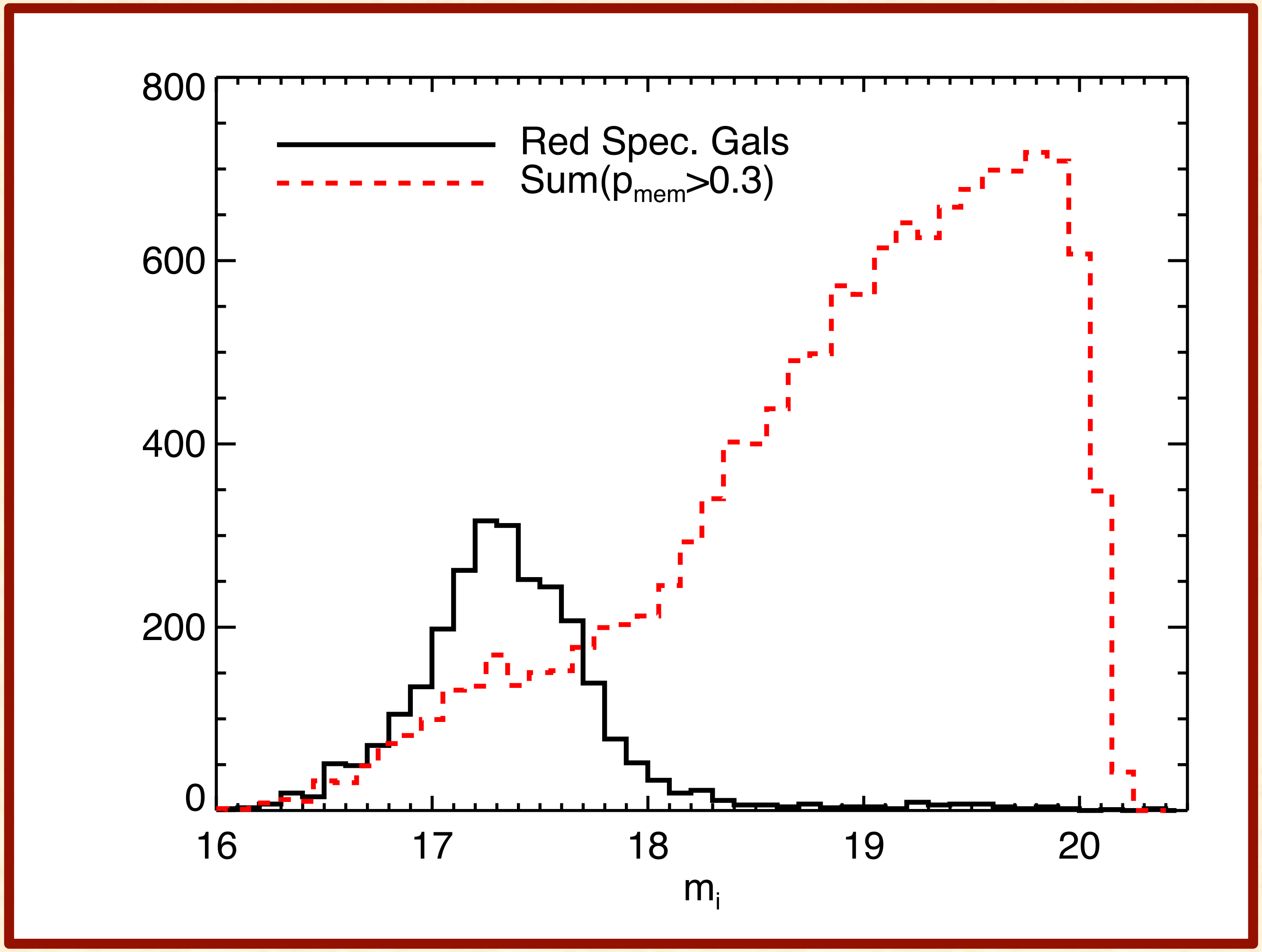
Assign spectra to all member galaxies.

Use photometry membership to create a large pseudo-spectroscopic (PS) training sample!

Use PS sample to constrain red-sequence model.

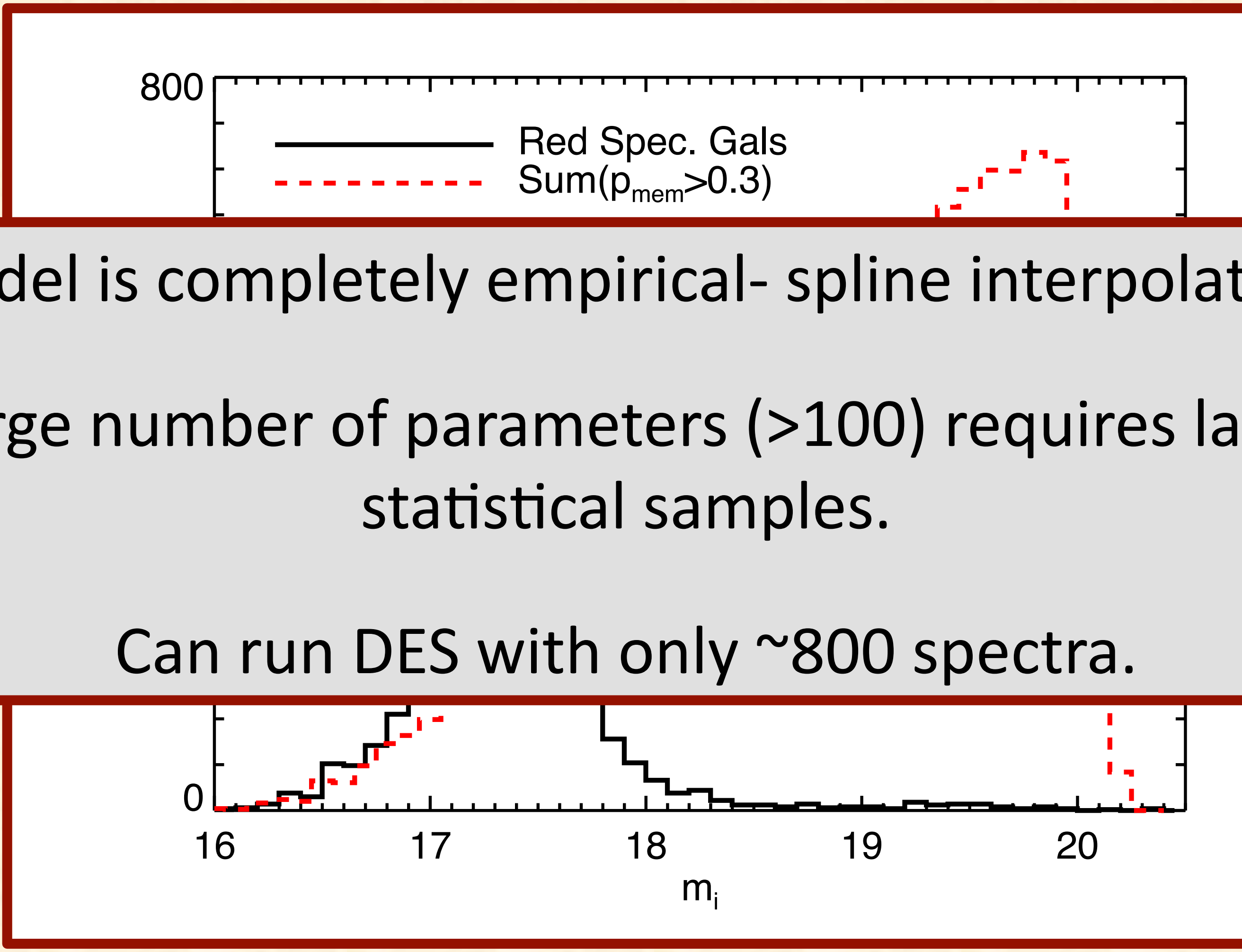
Iterate on model to self-train red-sequence.

Why Is Self-Training Valuable?



Leverages ***small non-representative*** spectroscopic galaxies to produce a ***large representative*** training set.

Why Is Self-Training Valuable?



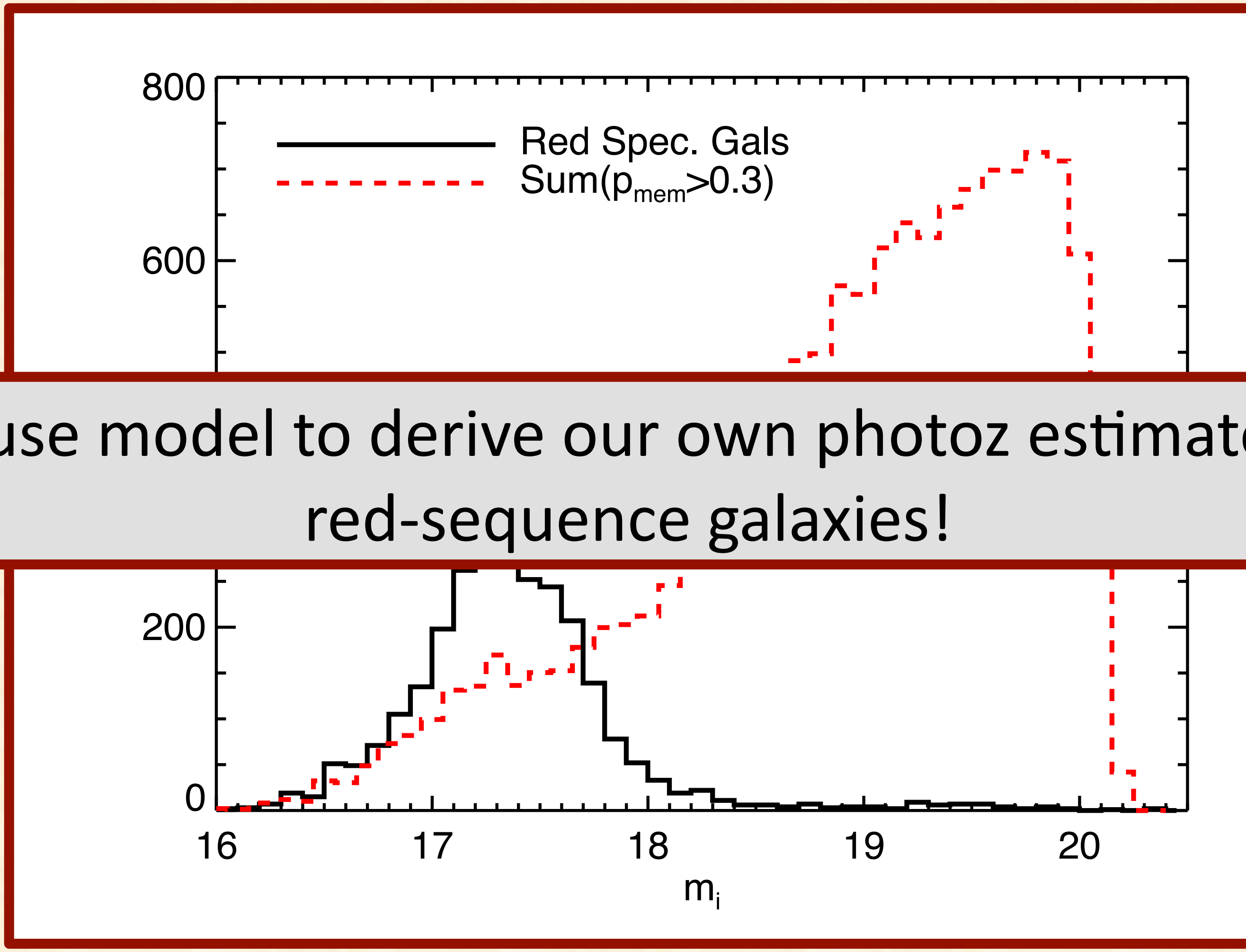
Model is completely empirical- spline interpolation.

Large number of parameters (>100) requires large statistical samples.

Can run DES with only ~800 spectra.

Leverage ***small non-representative*** spectroscopic galaxies to produce a ***large representative*** training set.

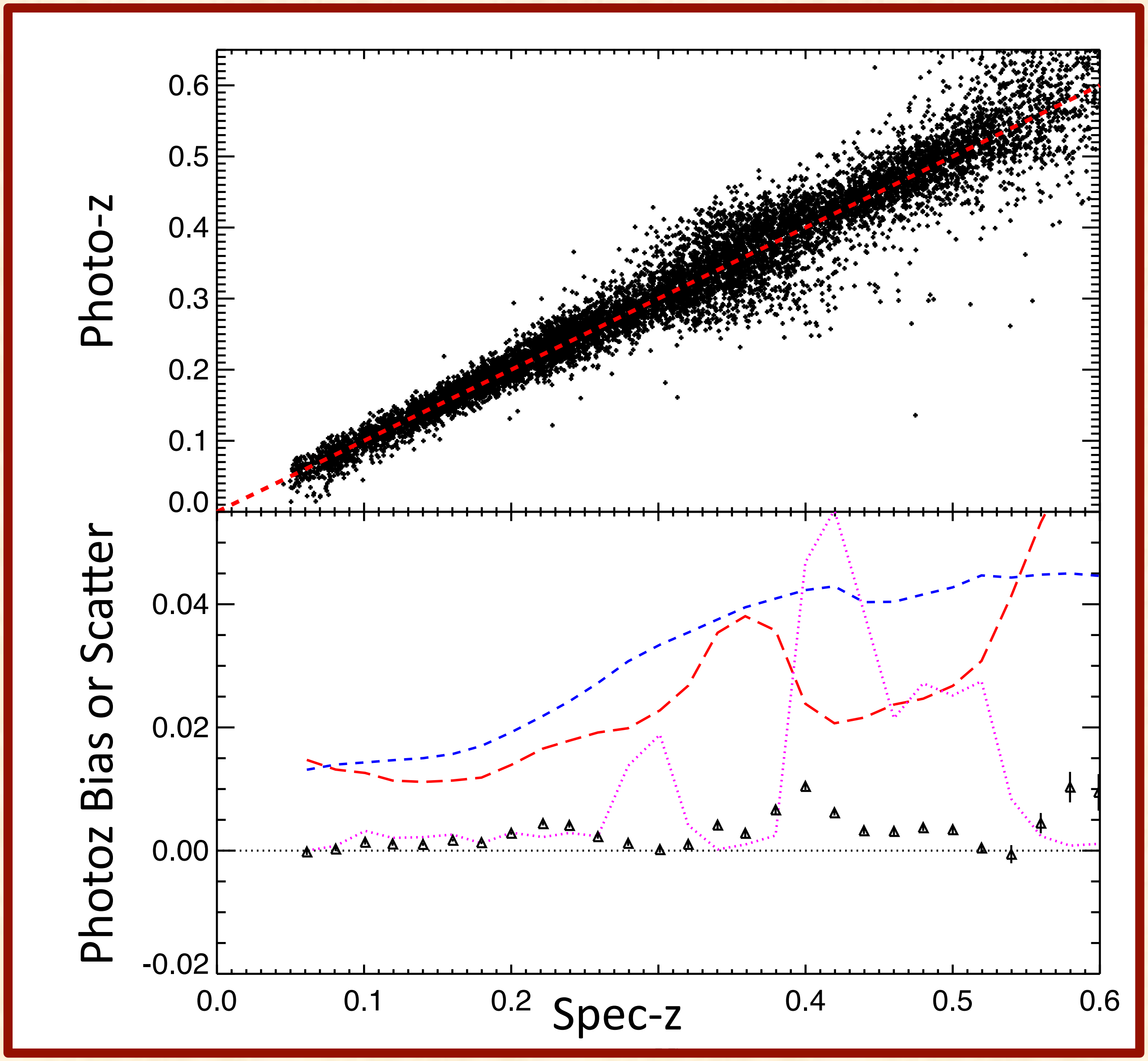
Why Is Self-Training Valuable?



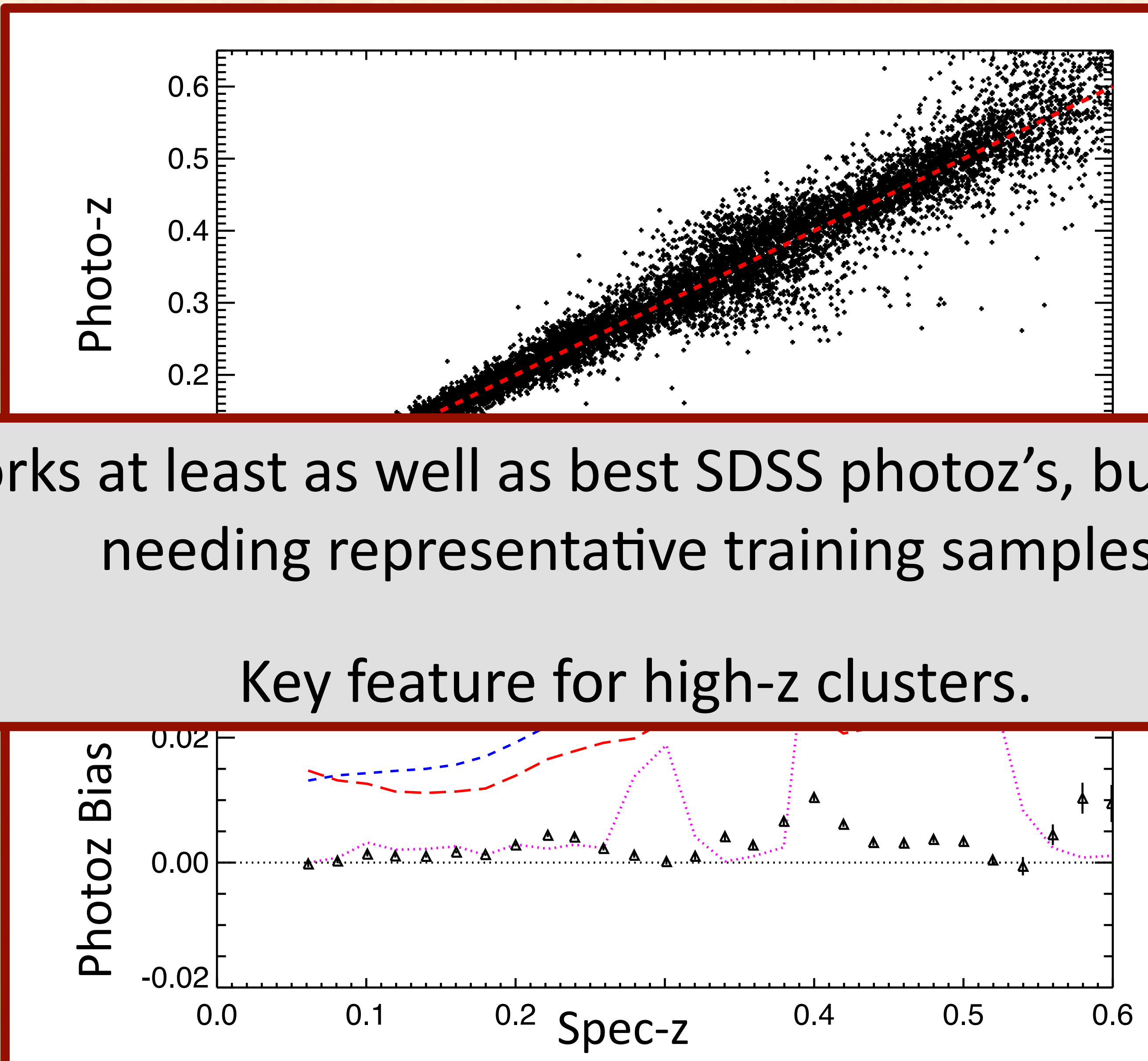
Can use model to derive our own photoz estimator for red-sequence galaxies!

Leverage ***small non-representative*** spectroscopic galaxies to produce a ***large representative*** training set.

redMaPPer Galaxy Photoz



redMaPPer Galaxy Photoz



Works at least as well as best SDSS photoz's, but w/out needing representative training samples.

Key feature for high-z clusters.

Cluster Finder

Take initial cluster redshift estimate (galaxy photoz).

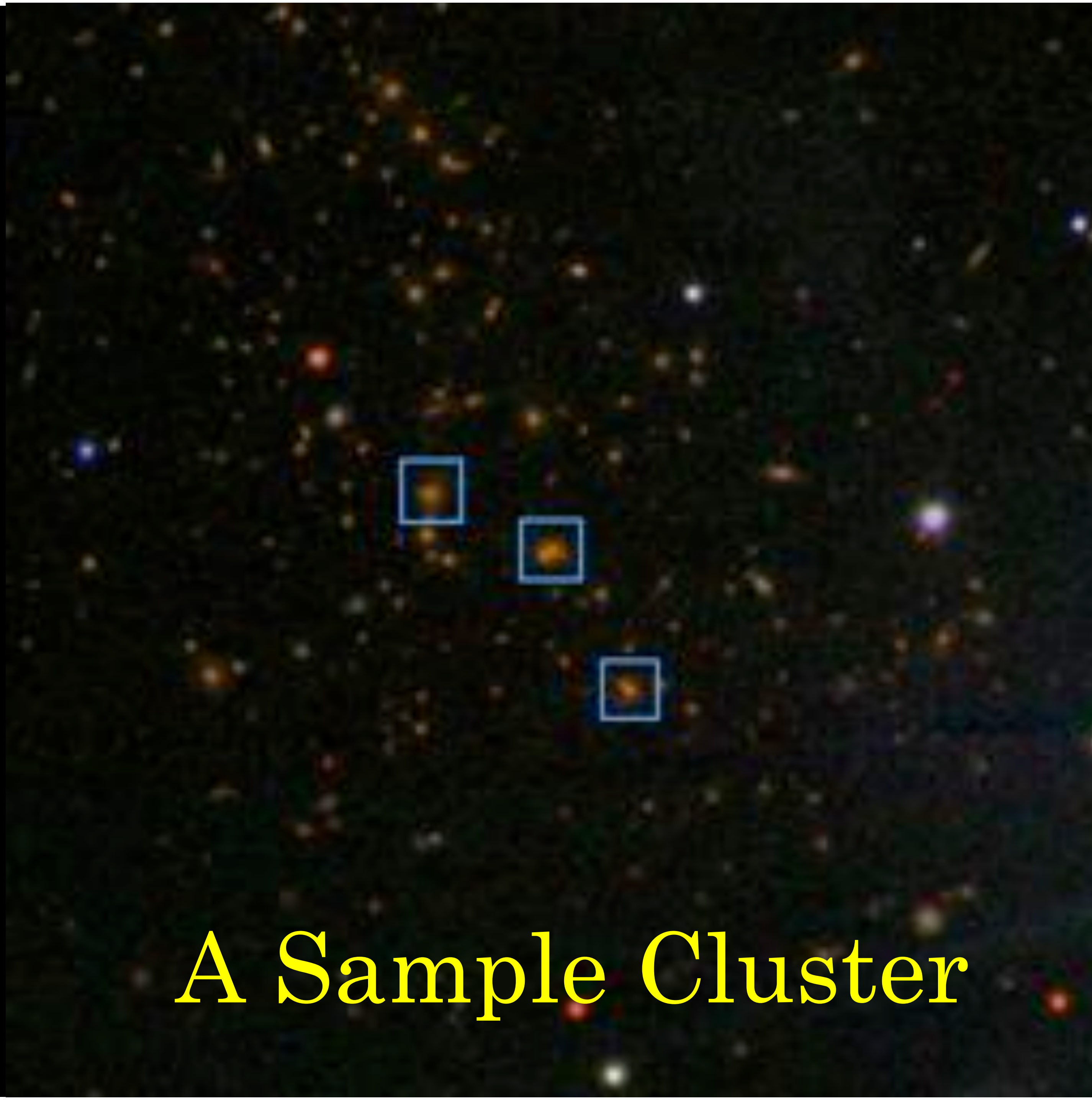
Use red-sequence model to estimate membership probability of galaxies and cluster richness:

$$p = \frac{\lambda u}{\lambda u + b} = \frac{Cluster\ Galaxy\ Density}{Total\ Galaxy\ Density} \qquad \lambda = \sum p$$

Simultaneously fit all high probability galaxies with a single red-sequence model to find cluster redshift.

Iterate.

Performance Tests in DR8


A Sample Cluster


A Sample Cluster

Performance: redshifts

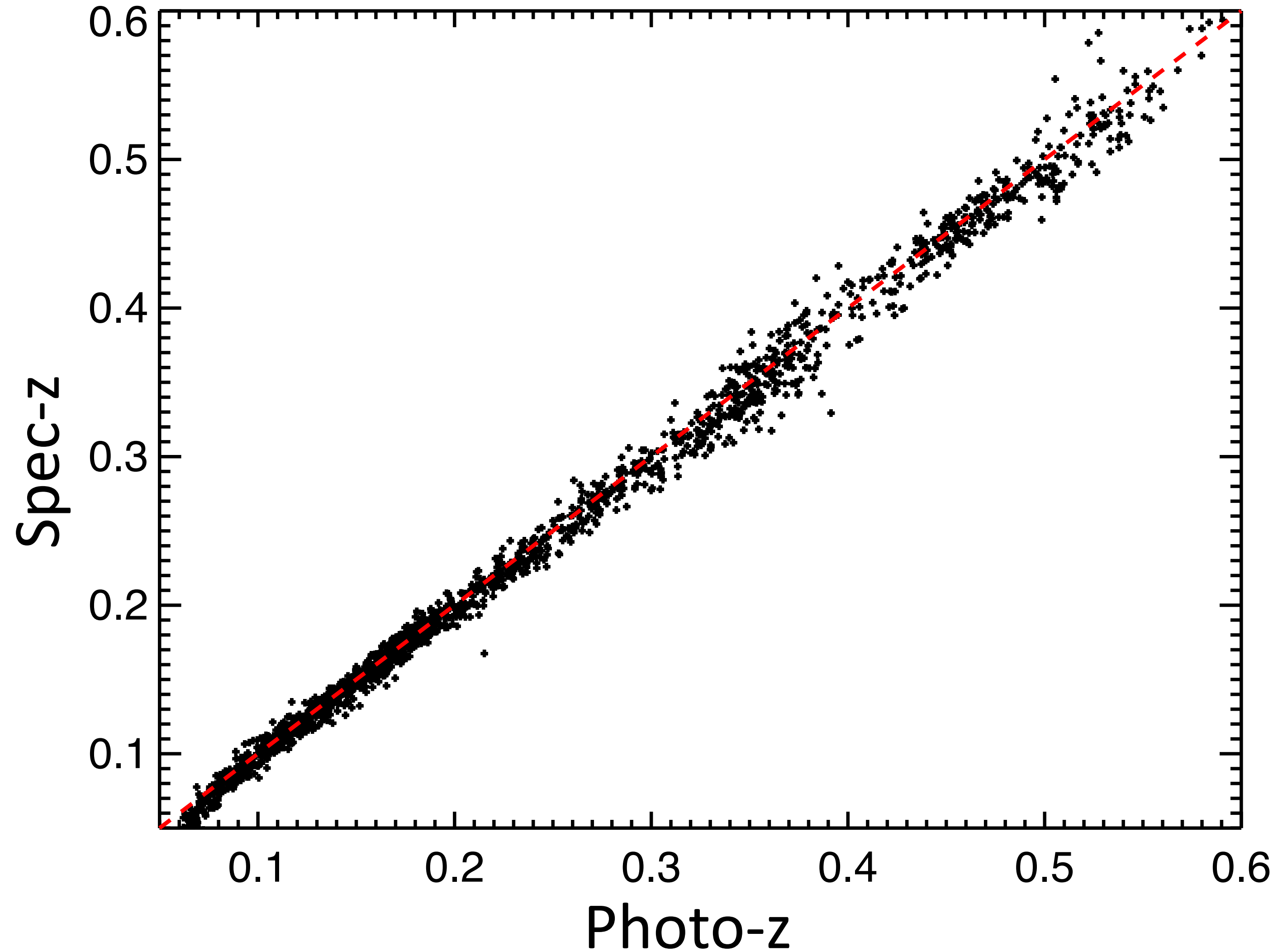
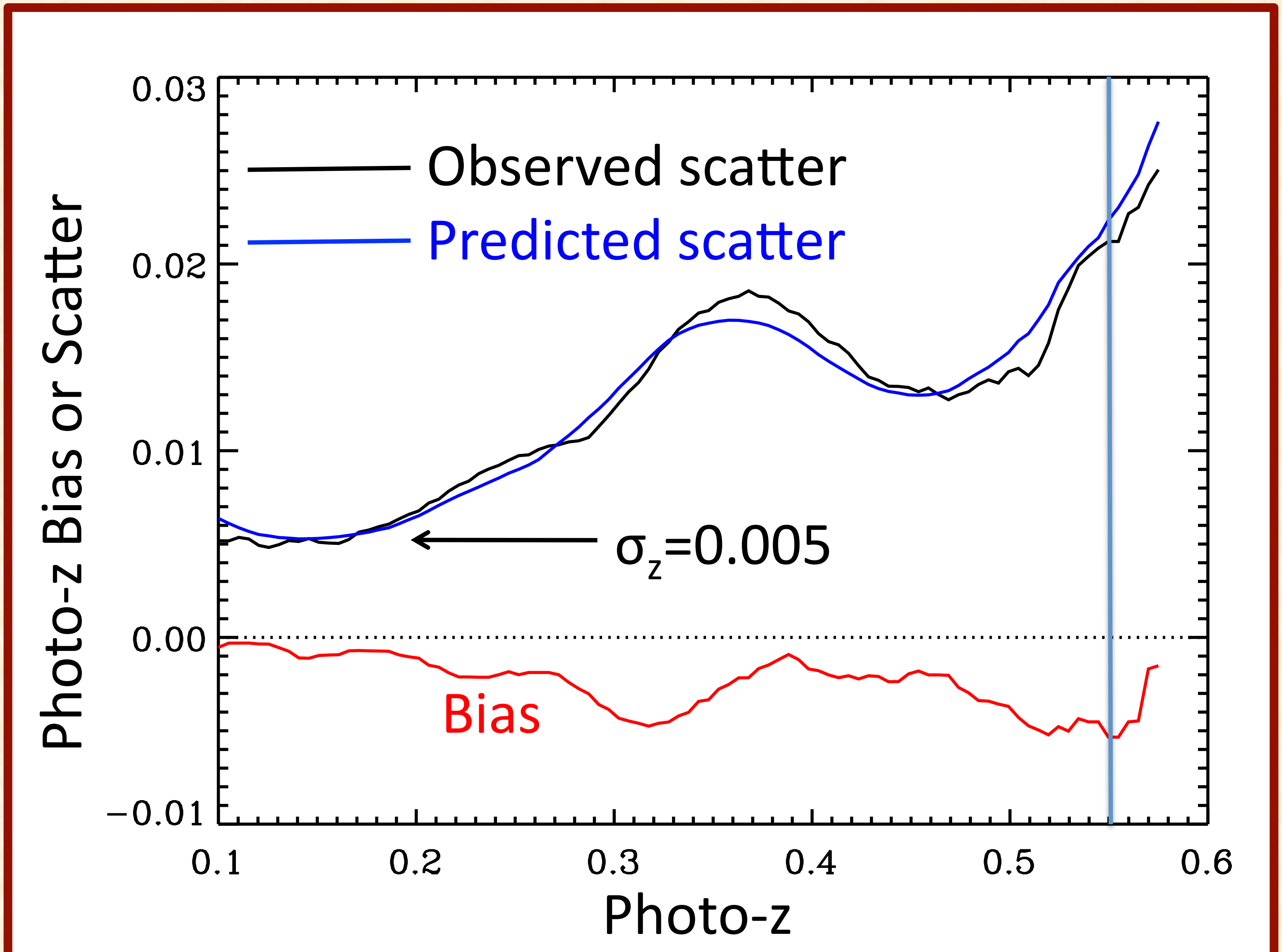


Photo-z Bias and Scatter



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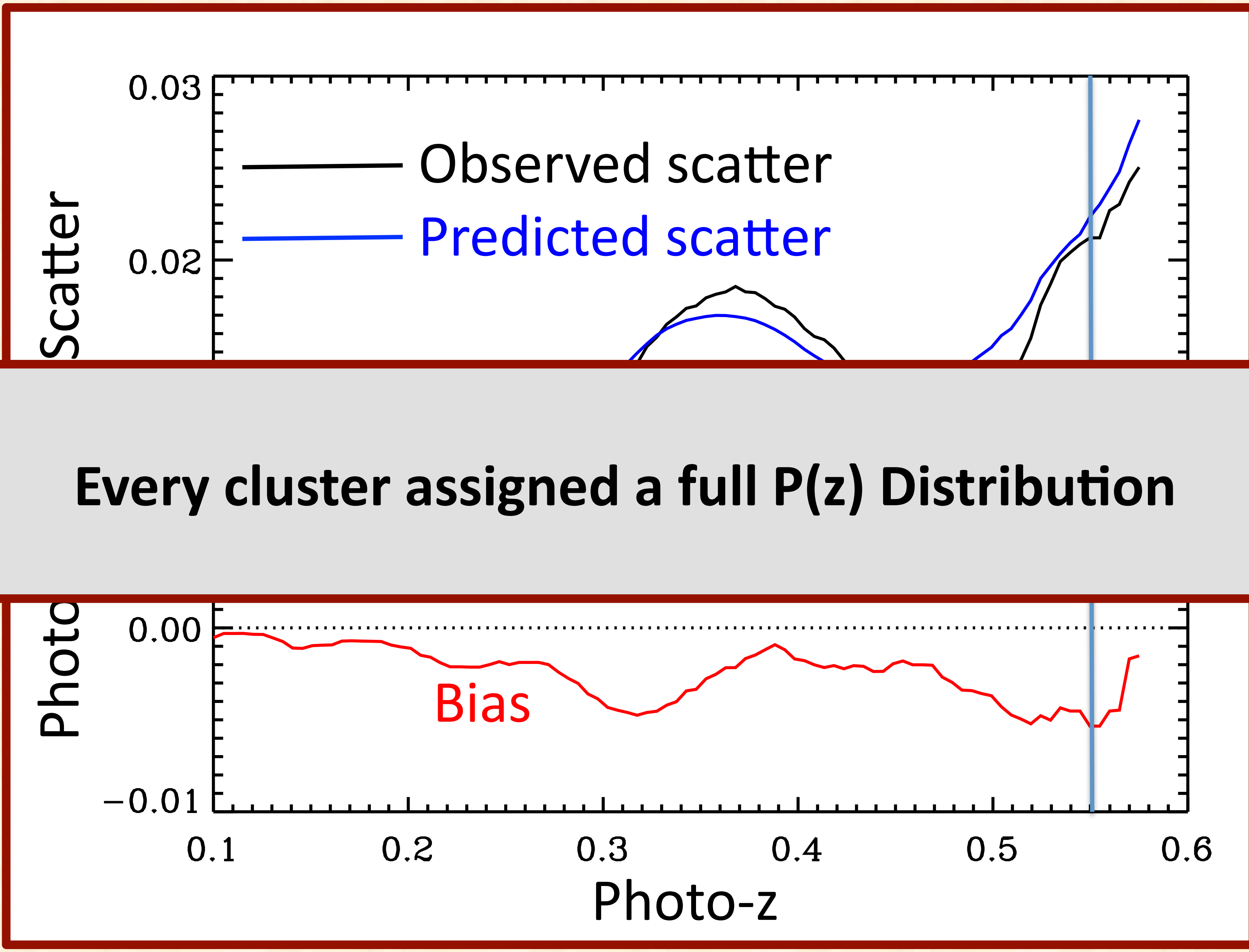
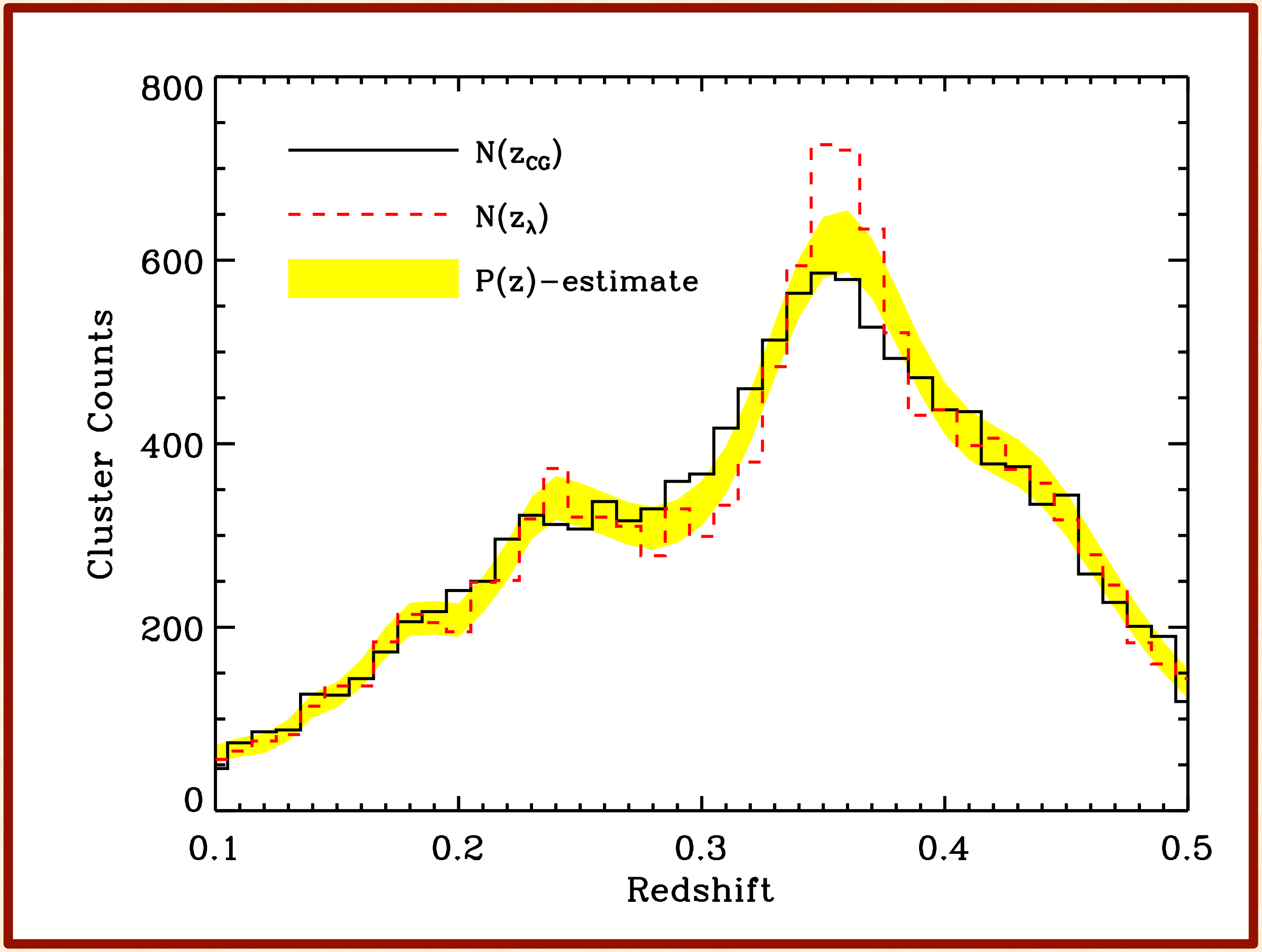
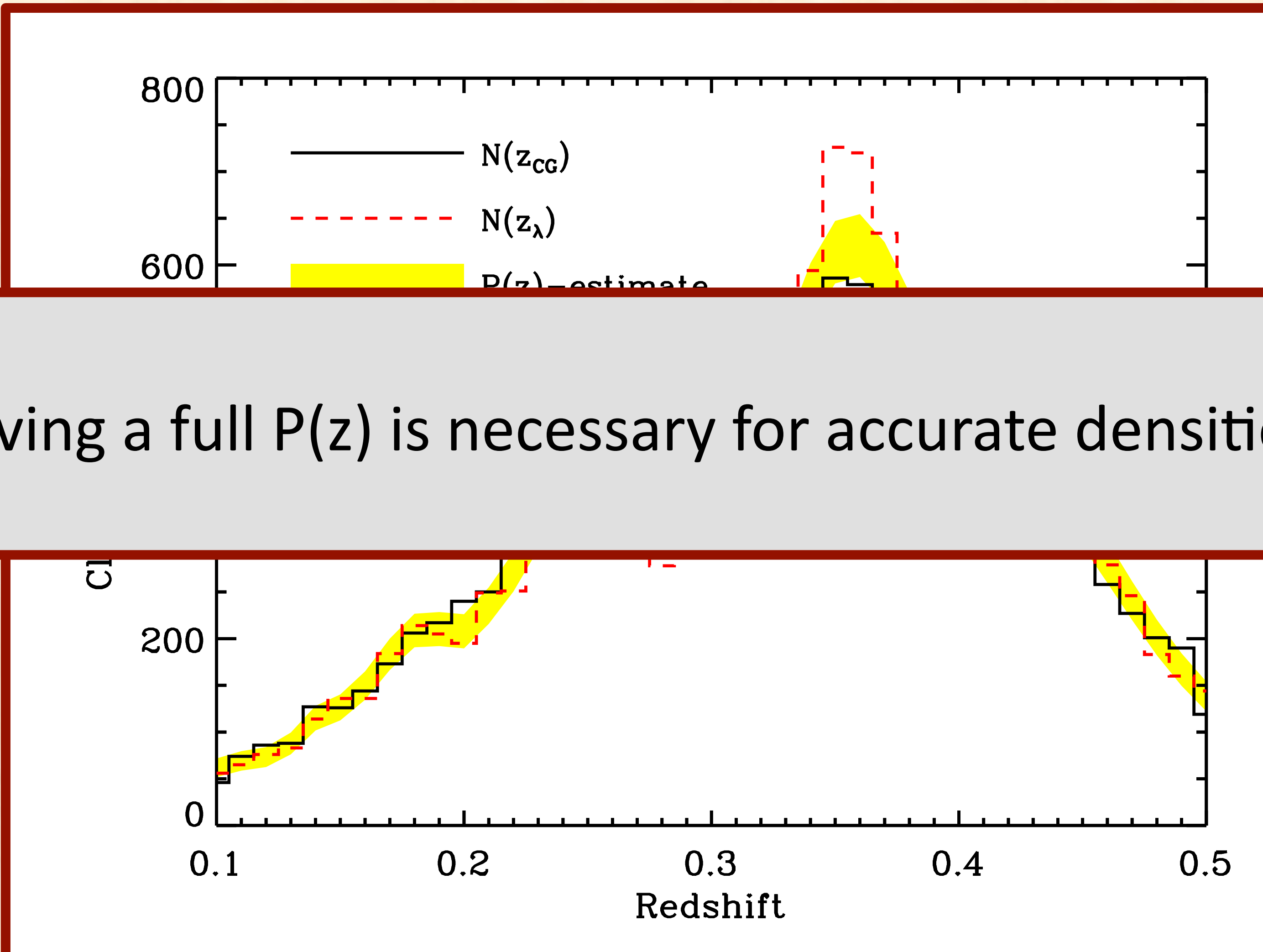


Every cluster assigned a full P(z) Distribution

P(z) Densities Match Spectroscopy

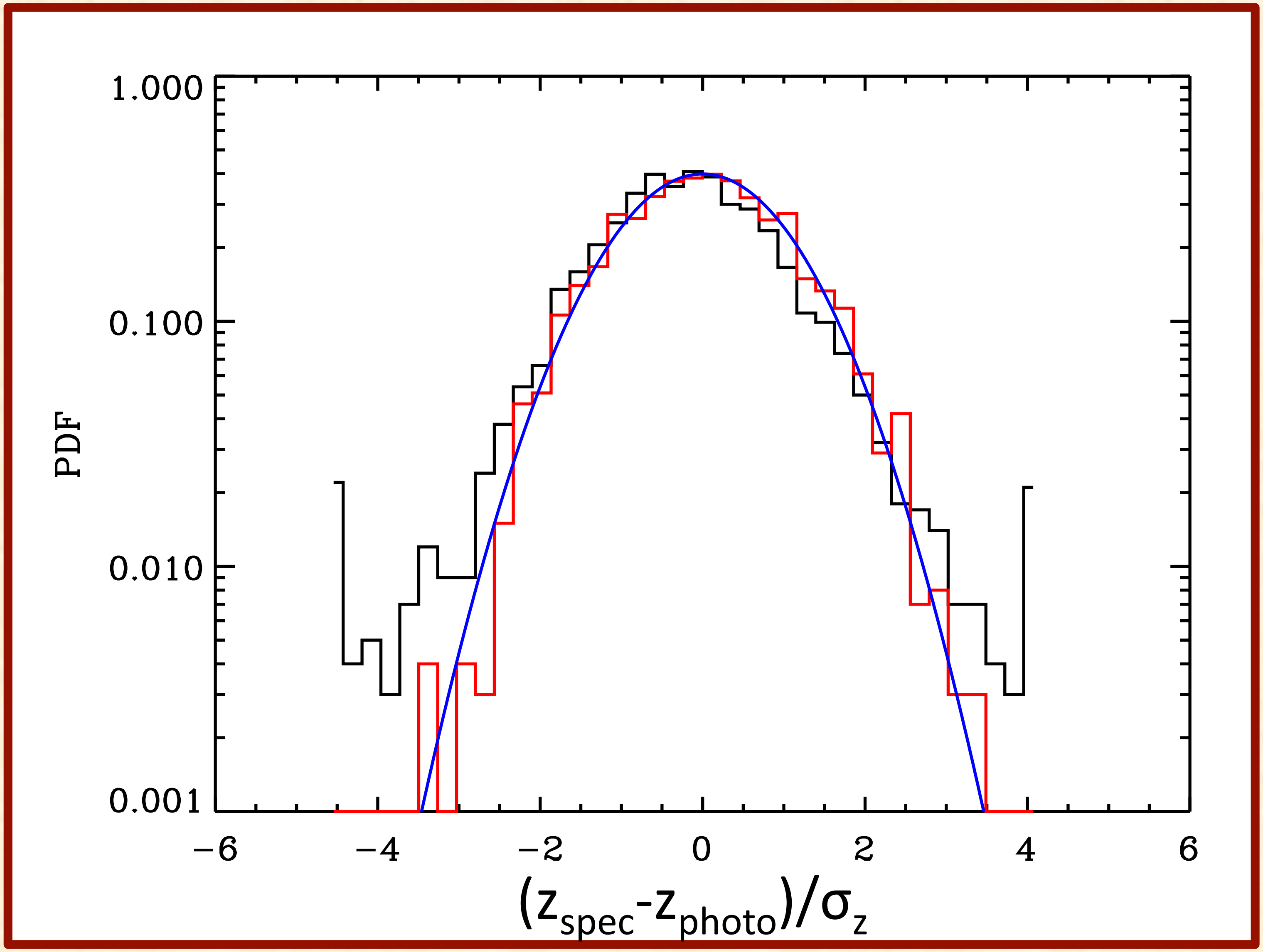


P(z) Densities Match Spectroscopy



Having a full P(z) is necessary for accurate densities!

Nearly Gaussian Photoz's



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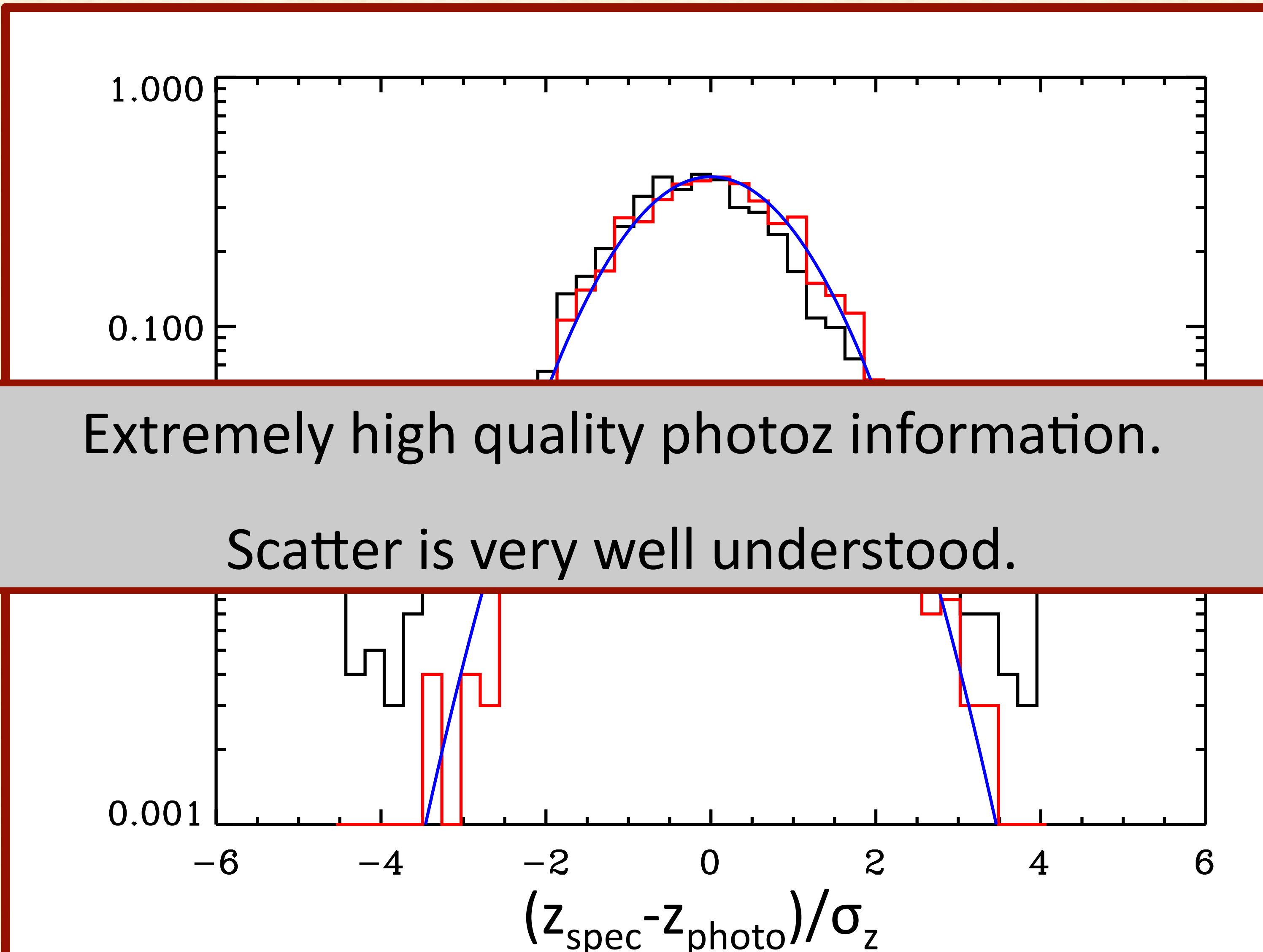
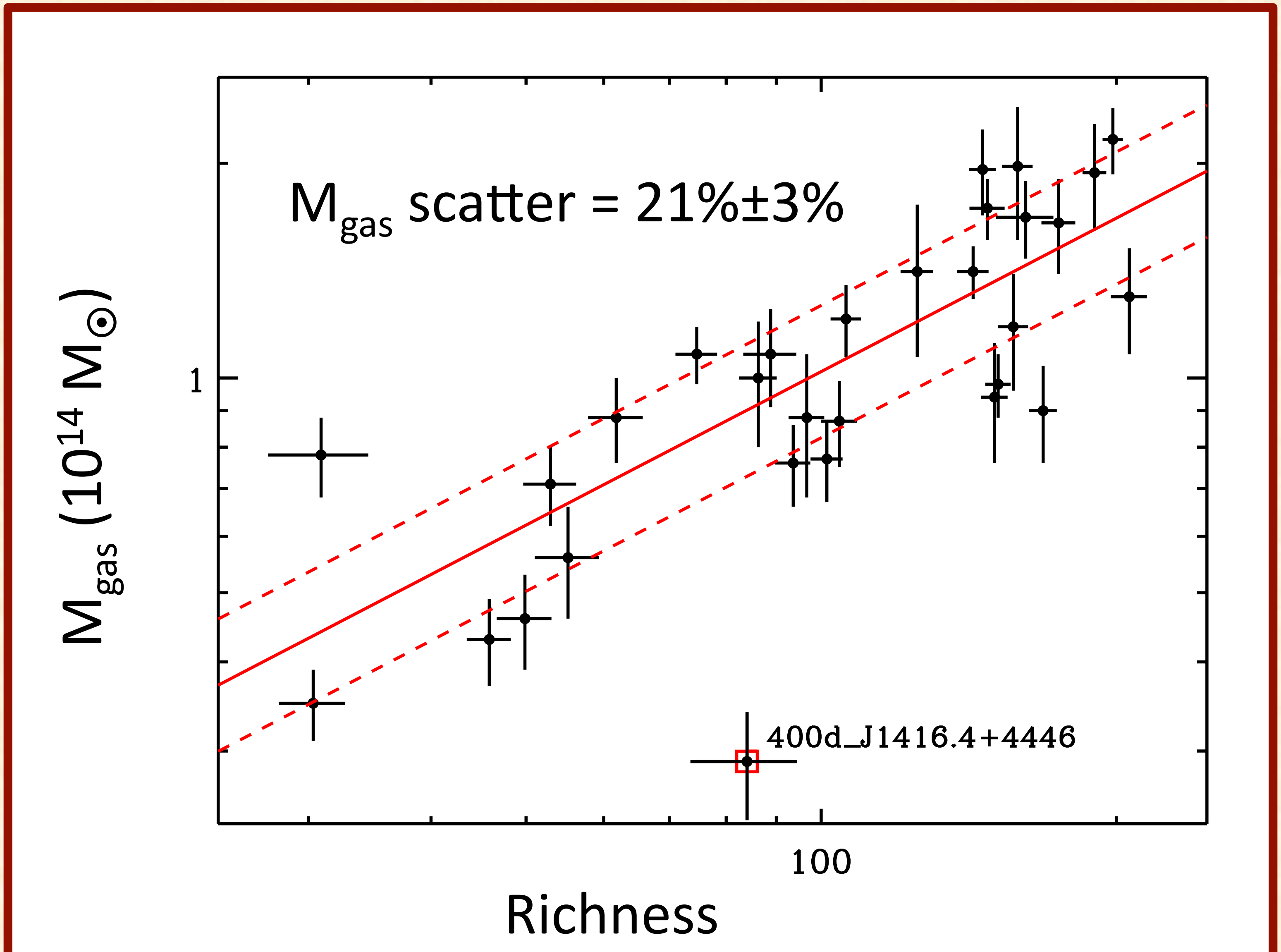


Extremely high quality photoz information.

Scatter is very well understood.

Low Scatter Mass Proxy



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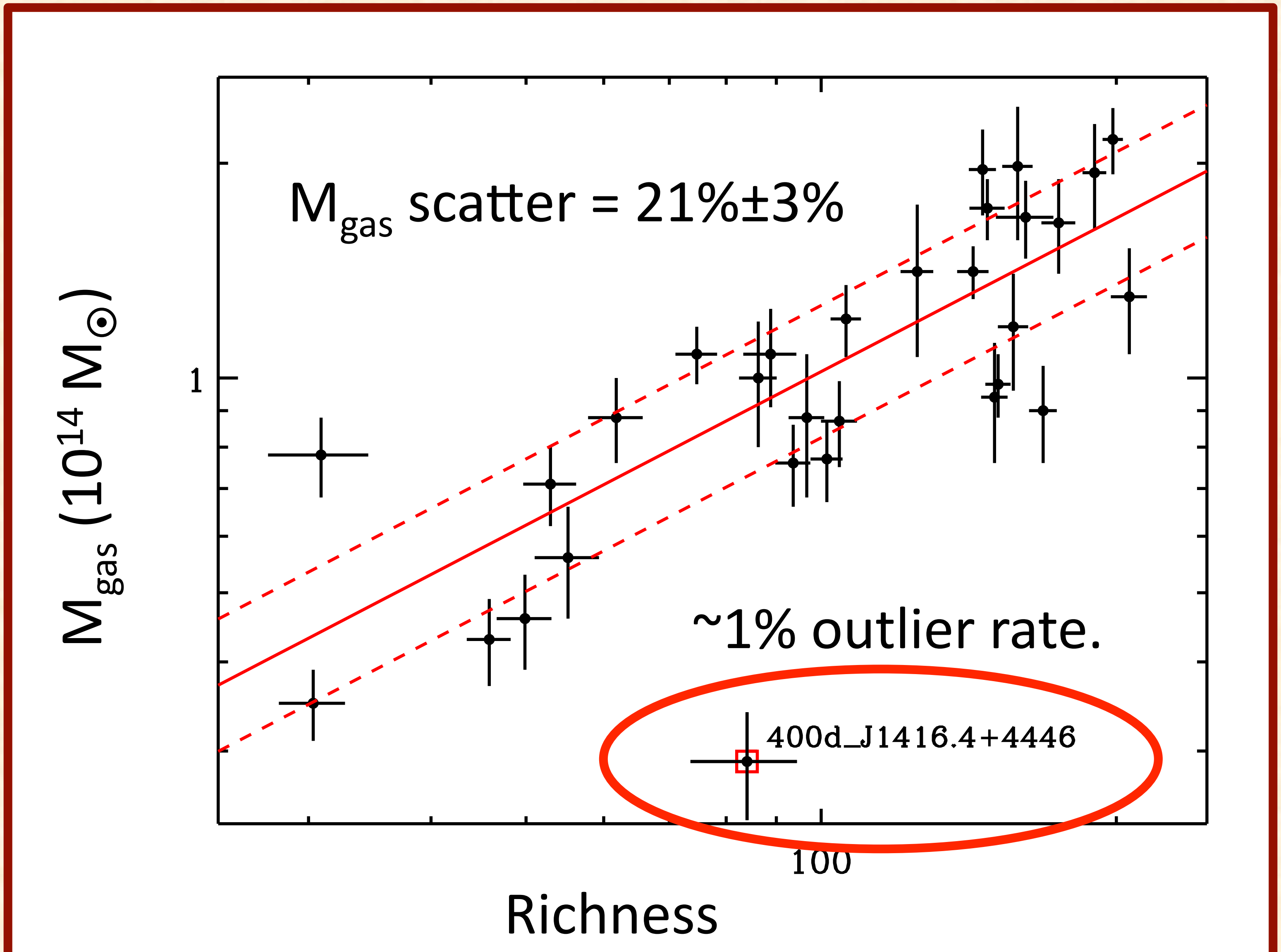
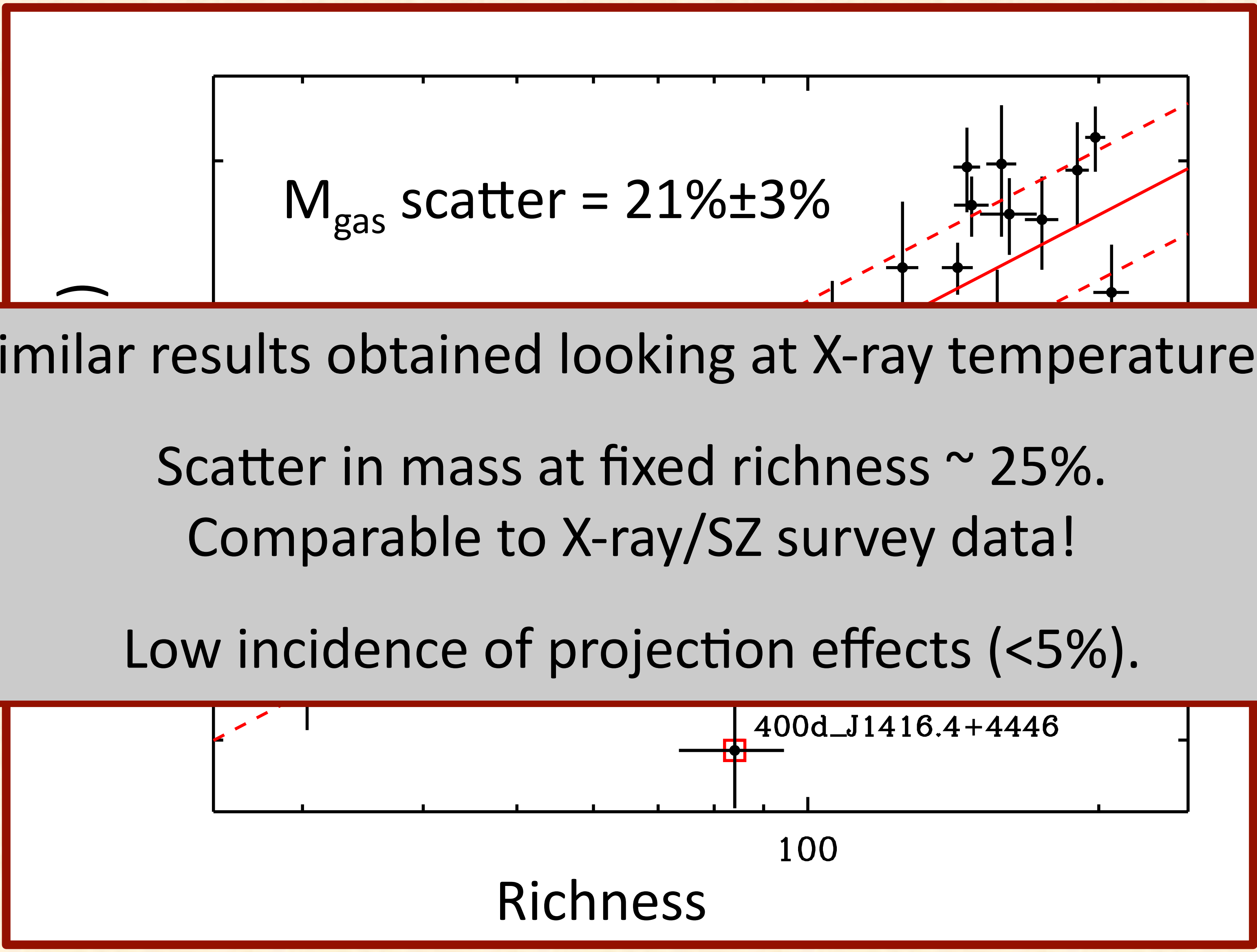


Low Scatter Mass Proxy



Similar results obtained looking at X-ray temperatures.

Scatter in mass at fixed richness ~ 25%.
Comparable to X-ray/SZ survey data!

Low incidence of projection effects (<5%).

Completeness and Purity

100% of all Planck and ACT clusters in SDSS found.

100% (90%) of all $L_X > 10^{44}$ ergs/s (10^{43} ergs/s) clusters found.

100% of all rich, low redshift clusters detected in X-rays.

X-ray detection limited only by RASS depth.

Can go into more detail at the end
if people really want me to.

Masking!

Can handle inhomogeneous masks (varying depth).

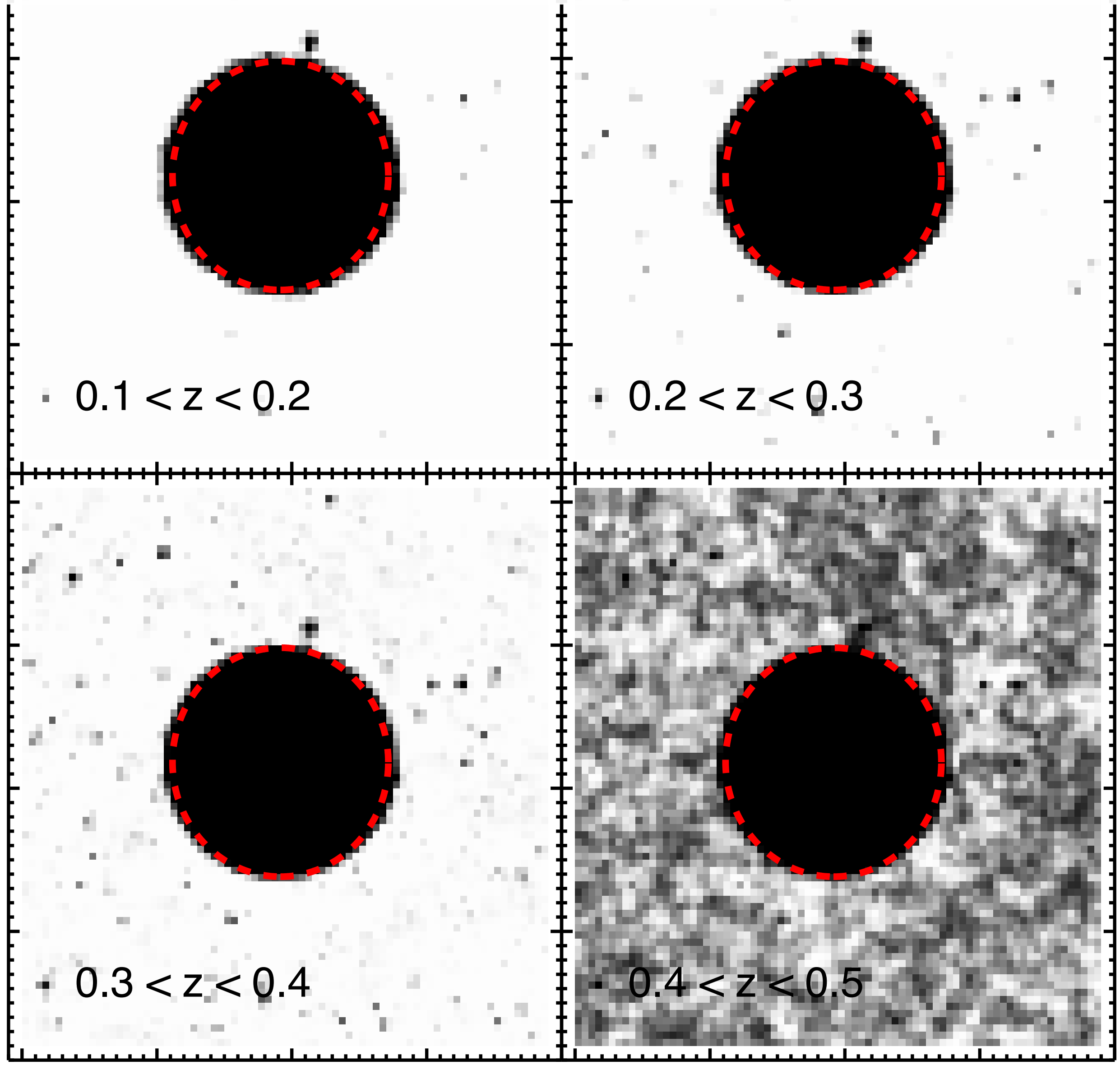
Generates full cluster-appropriate random points:

Place random point *with richness and redshift.*

Generate Monte Carlo realizations to determine detection probability.

Input richness = 40

Detection requirement: 20 galaxy counts



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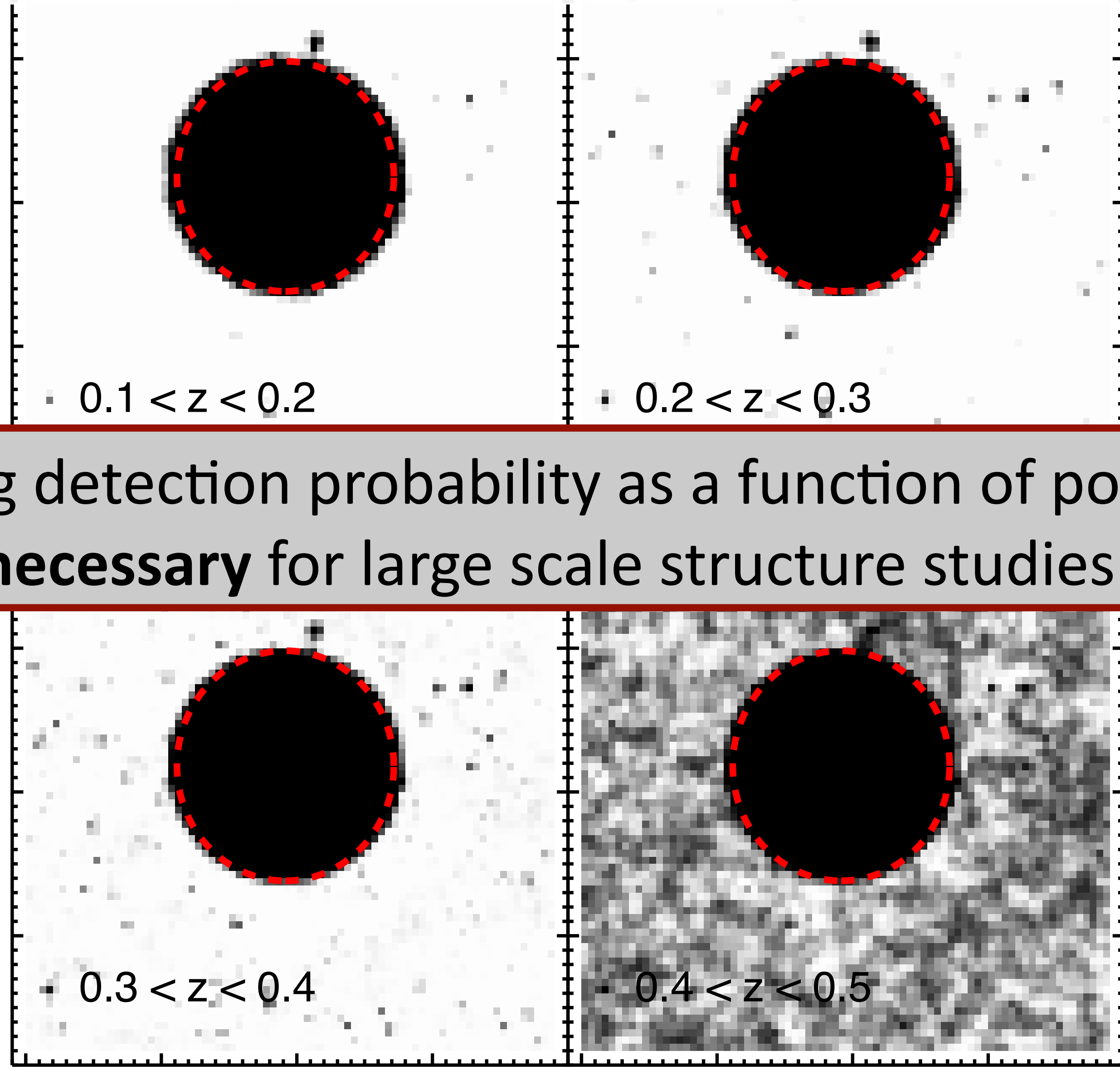


Knowing detection probability as a function of position is **necessary** for large scale structure studies.

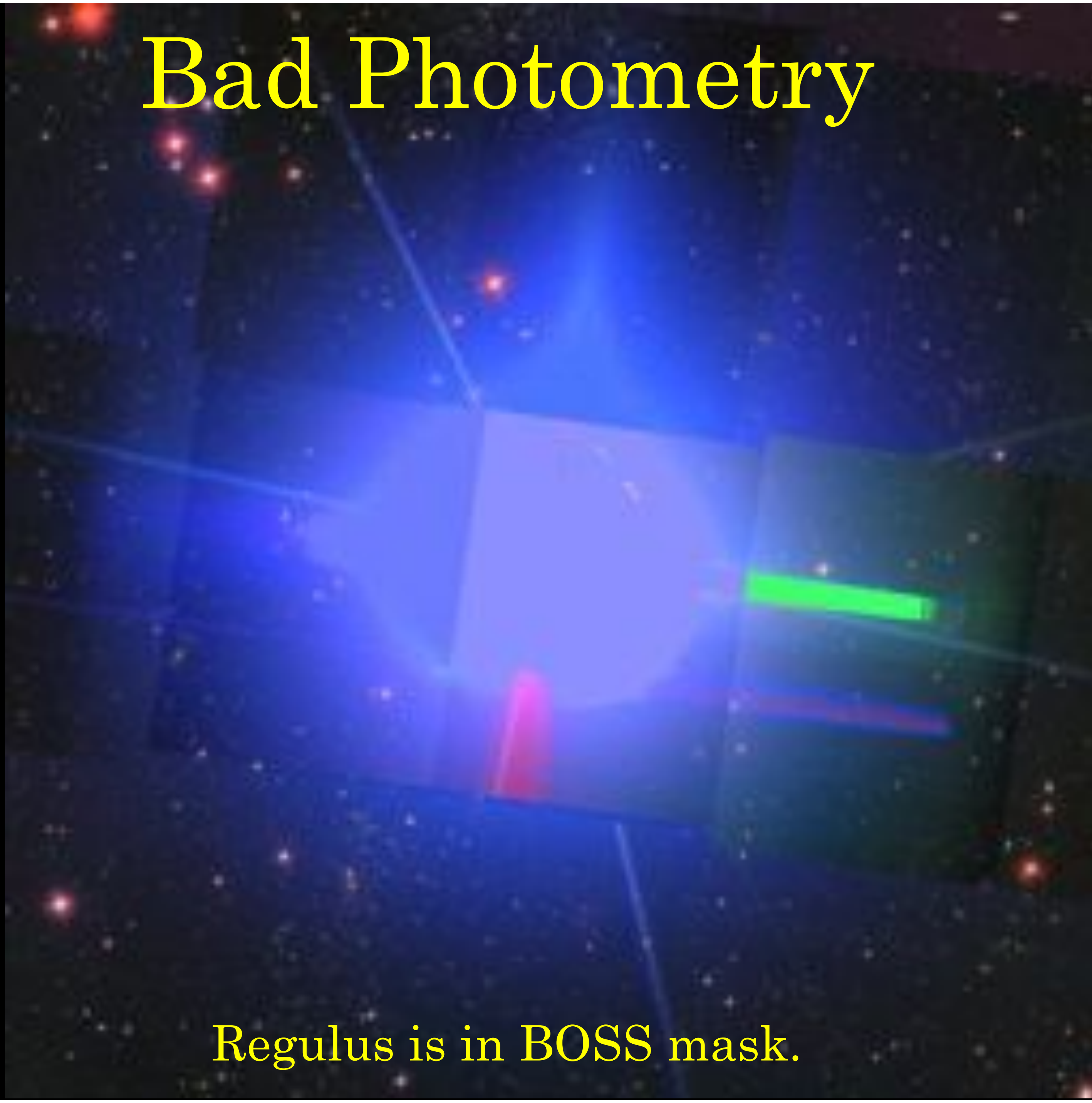
4: Things to Come out of redMaPPer

redMaPPer + X-ray/SZ Data are Good Tests of Photometry

Example no. 1: bad photometry in SDSS.

- bad photometry regions show up as outliers in optical-X-ray scaling relations.

Bad Photometry



Regulus is in BOSS mask.

redMaPPer + X-ray/SZ Data are Good Tests of Photometry

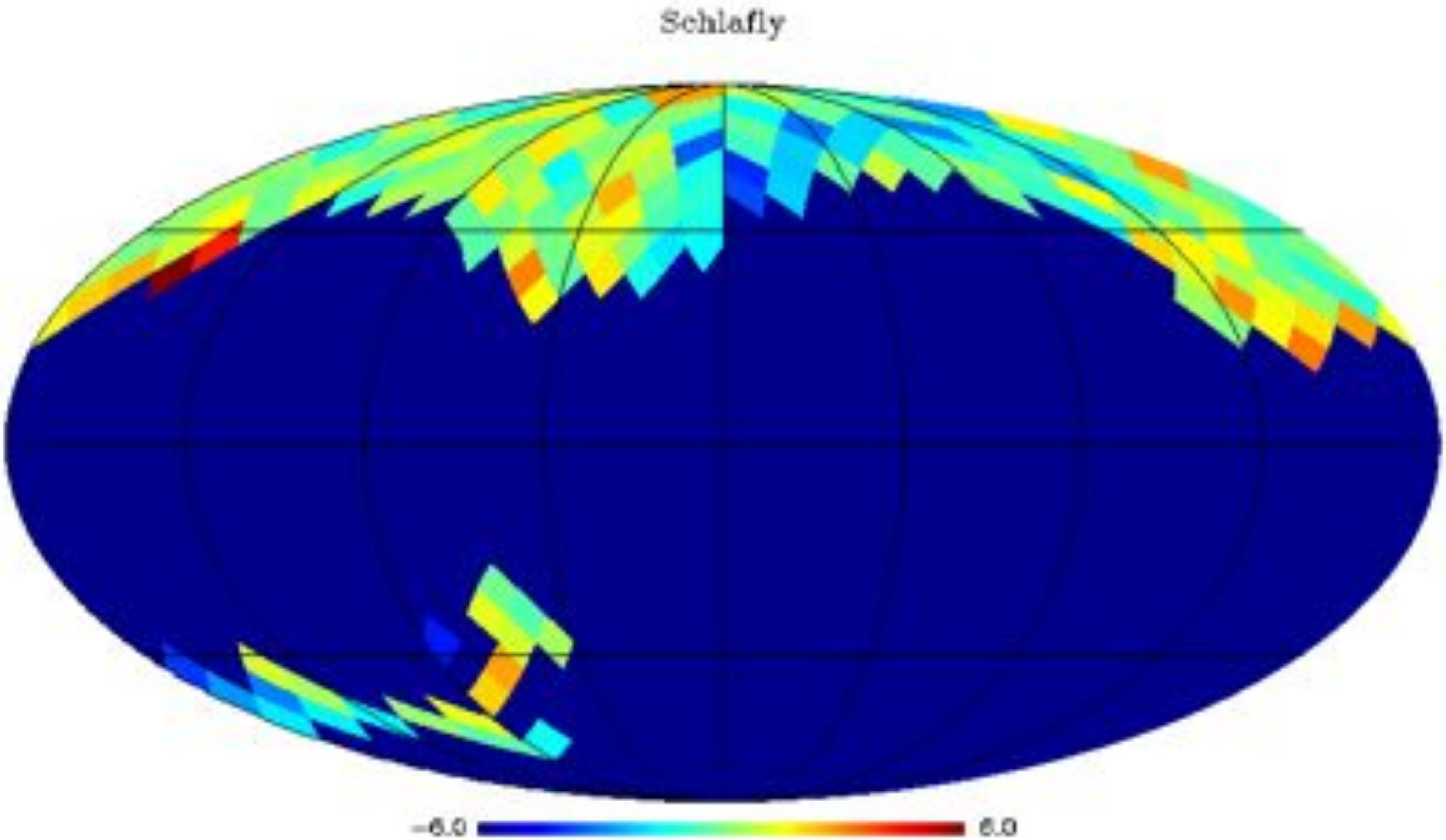
Example no. 1: bad photometry in SDSS.

- bad photometry regions show up as outliers in optical-X-ray scaling relations.

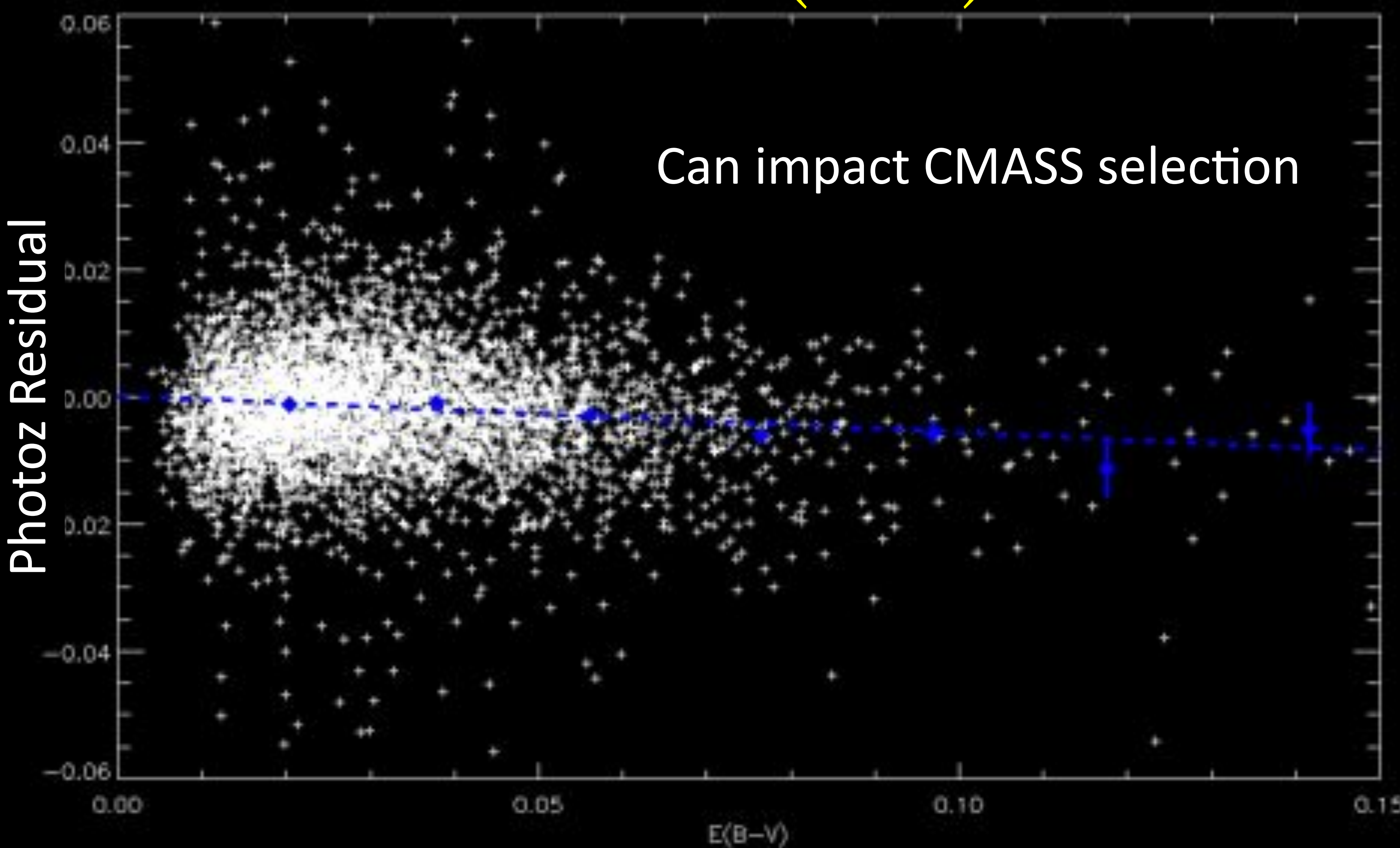
Example no. 2: dust redenning/calibration systematics.

- Photoz residuals from redMaPPer show structure!

Significance of Redshift Bias



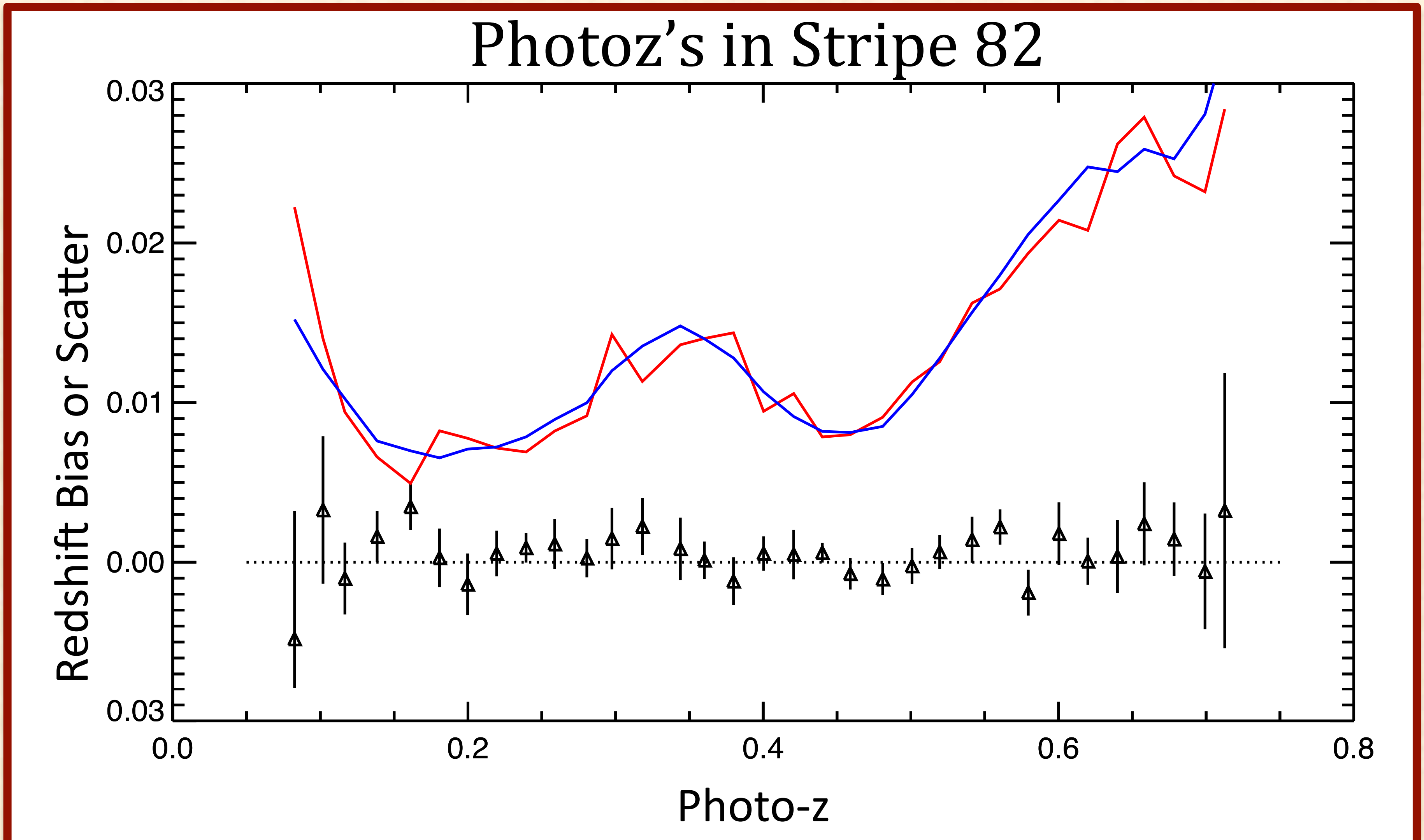
Photoz Resdiuals Correlate with E(B-V)



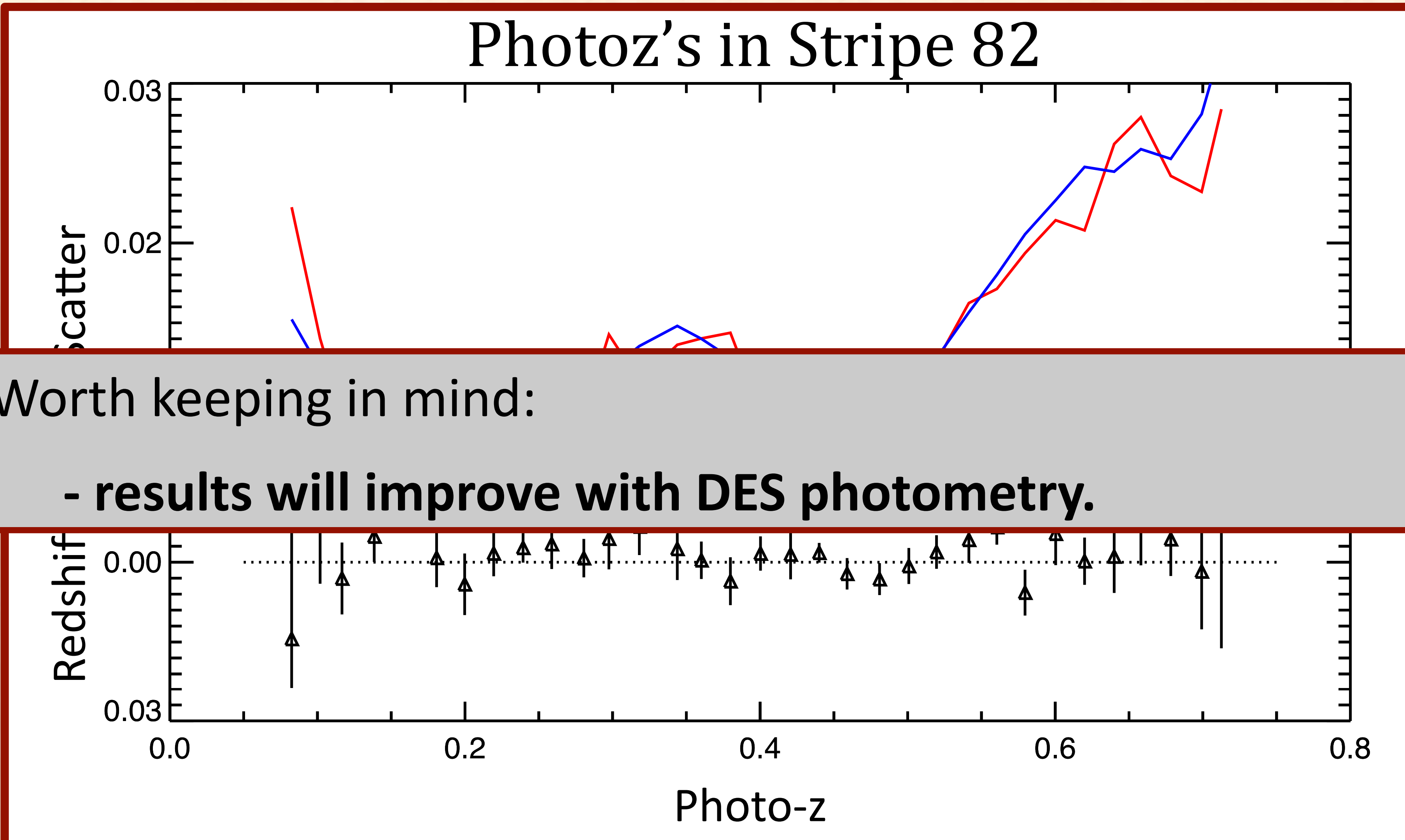
Crazy Idea

BAO with redMaPPer Clusters!

Why Do BAO with Clusters?



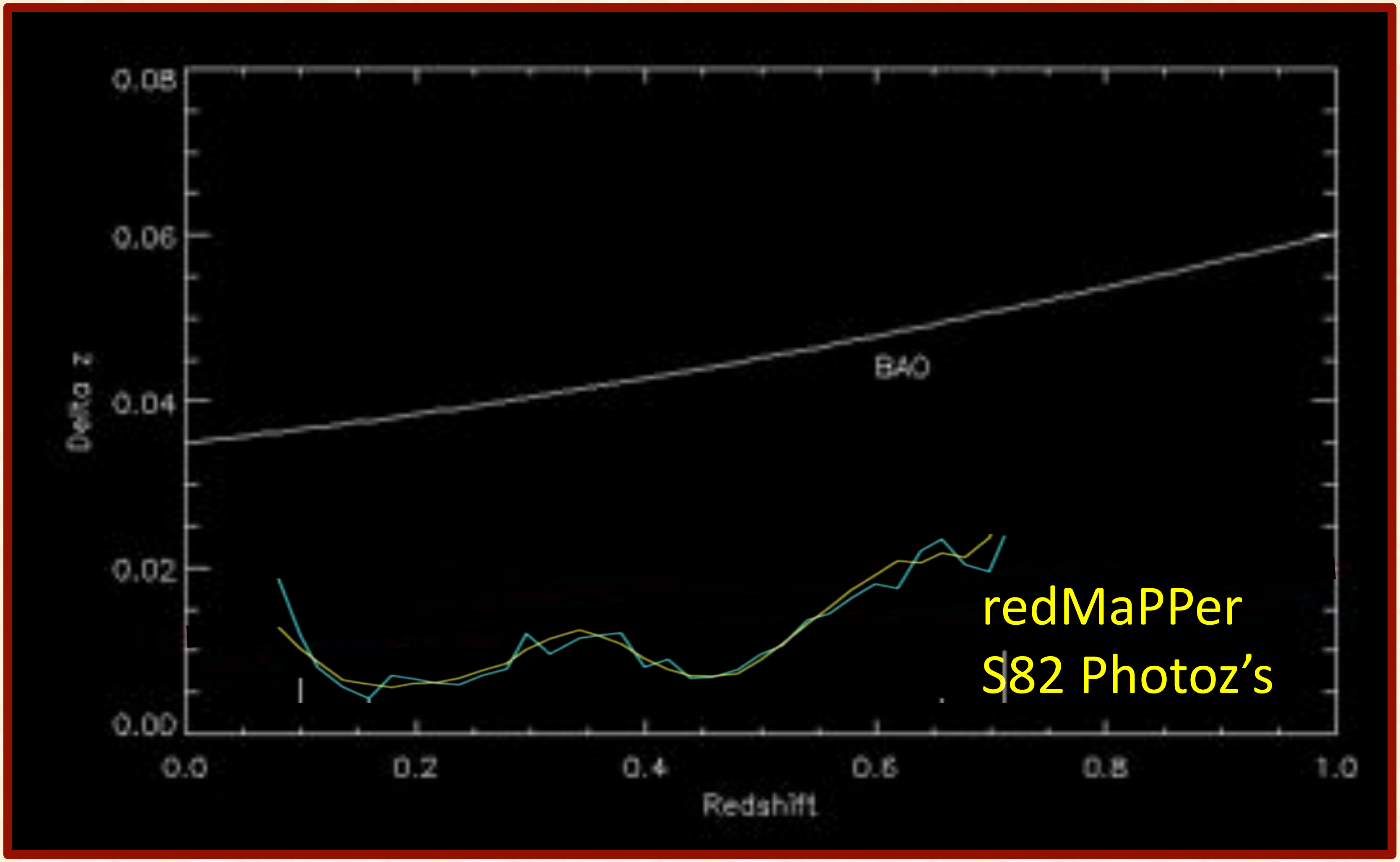
Why Do BAO with Clusters?



Worth keeping in mind:

- results will improve with DES photometry.

RM Photoz's are Well Below BAO Scale



The Problem with Cluster BAO

So what's the down side?

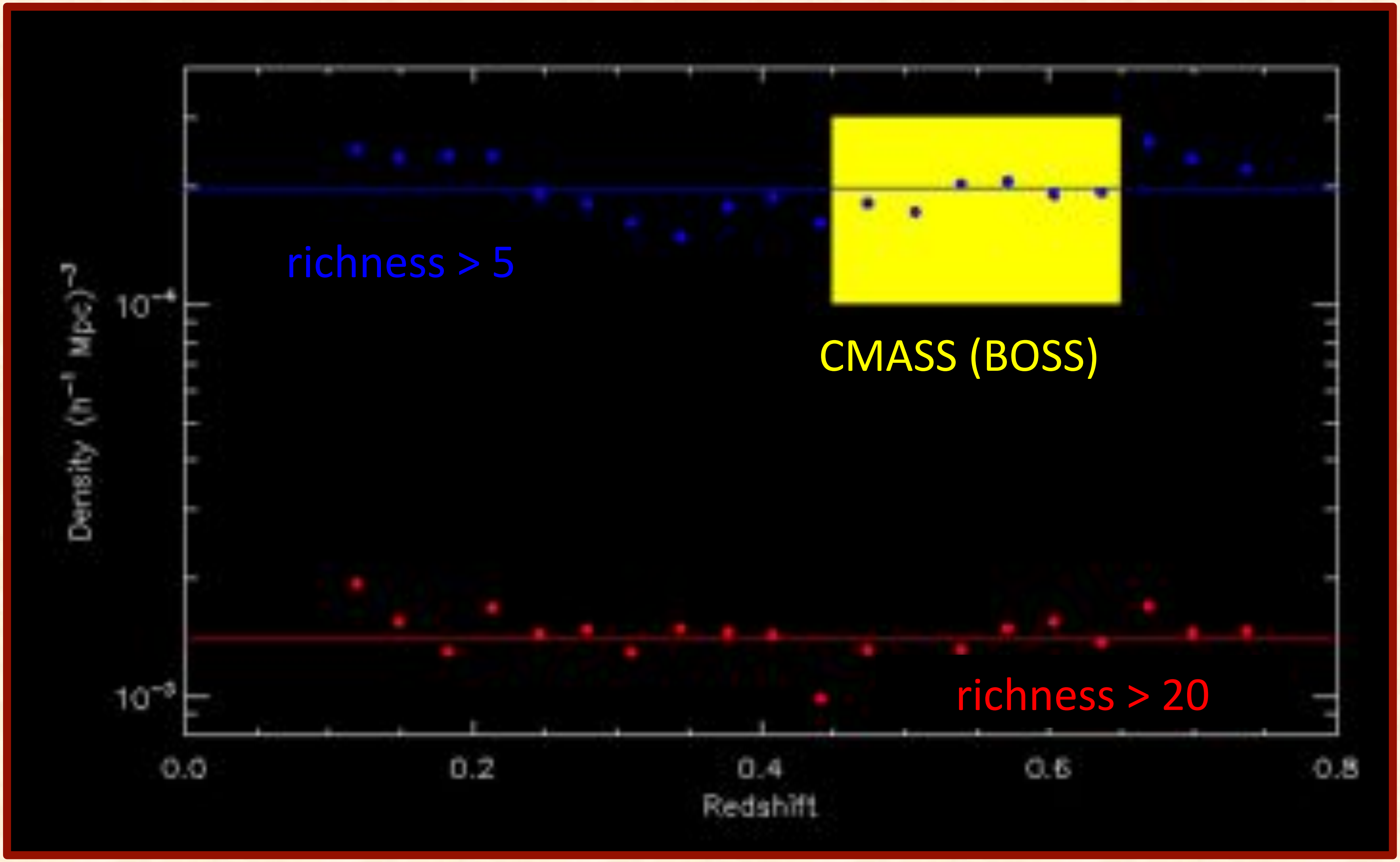
Low density: many fewer clusters than galaxies.

Solution:

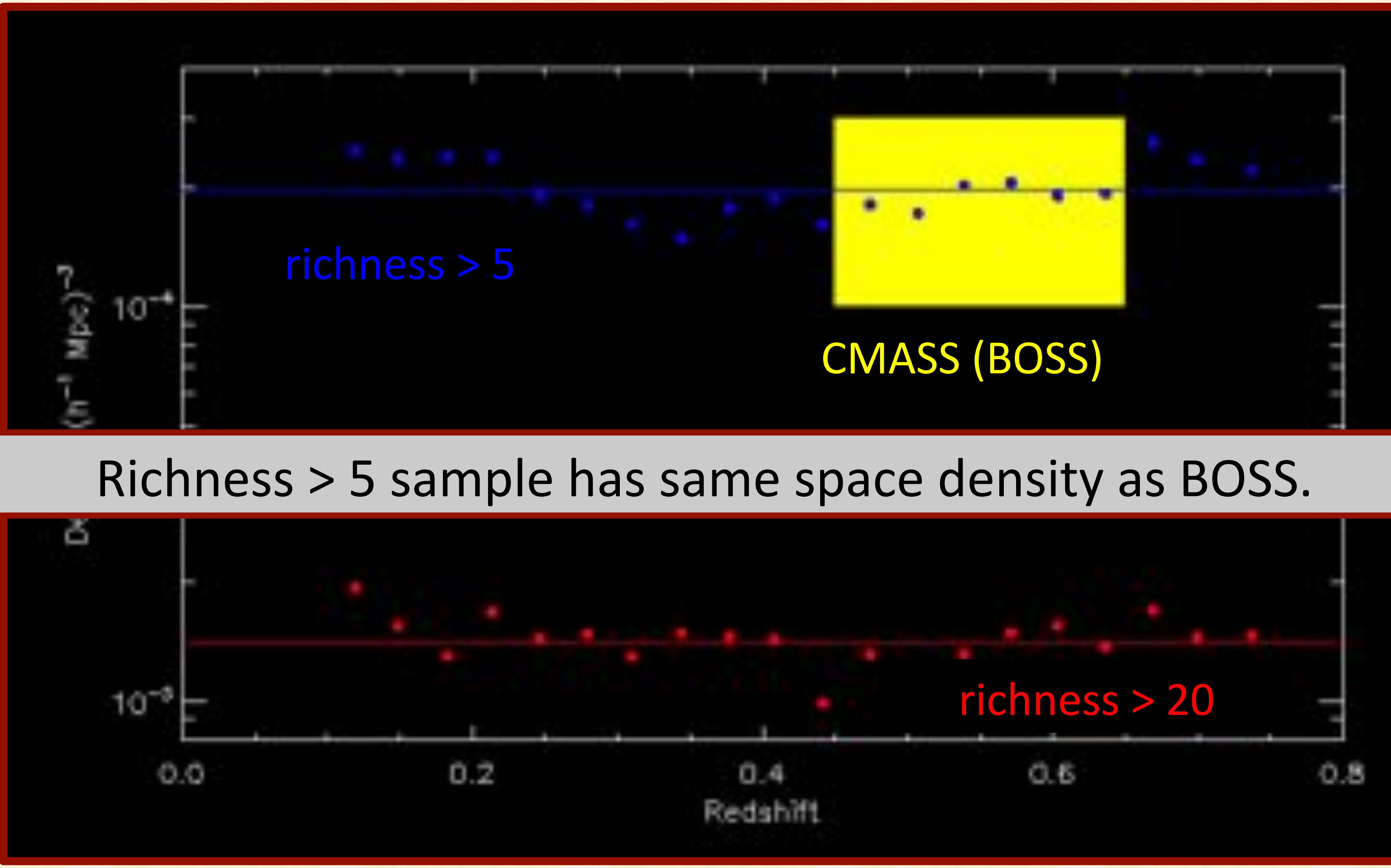
Just go to lower richness objects.

How low can you go?

redMaPPer Cluster Density



redMaPPer Cluster Density



Richness > 5 sample has same space density as BOSS.

Why Richness > 5 for BAO?

For cluster counting, expect to use richness > 20.

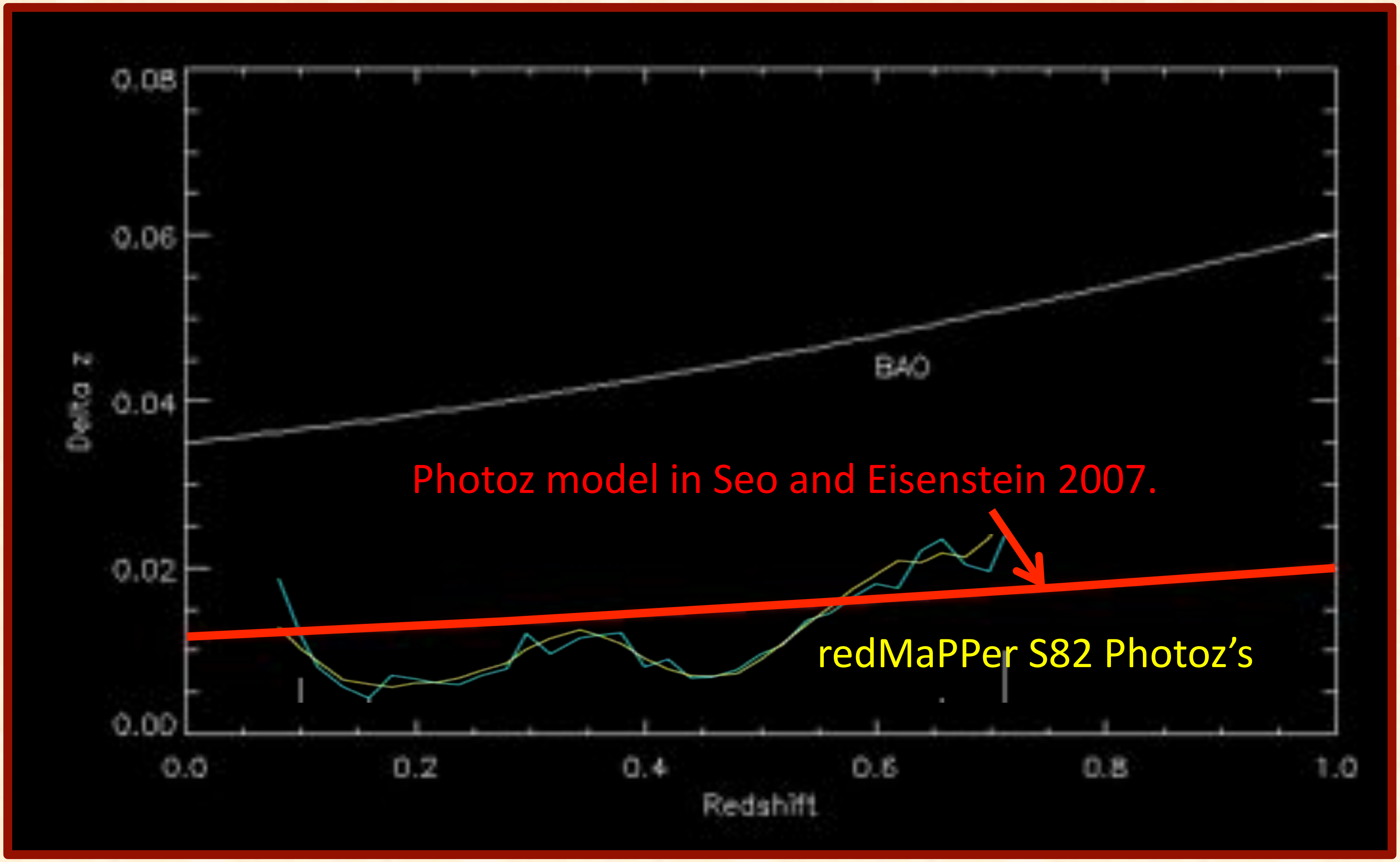
For richness < 20, larger fraction of projections.

Do not expect projections to impact BAO signal.

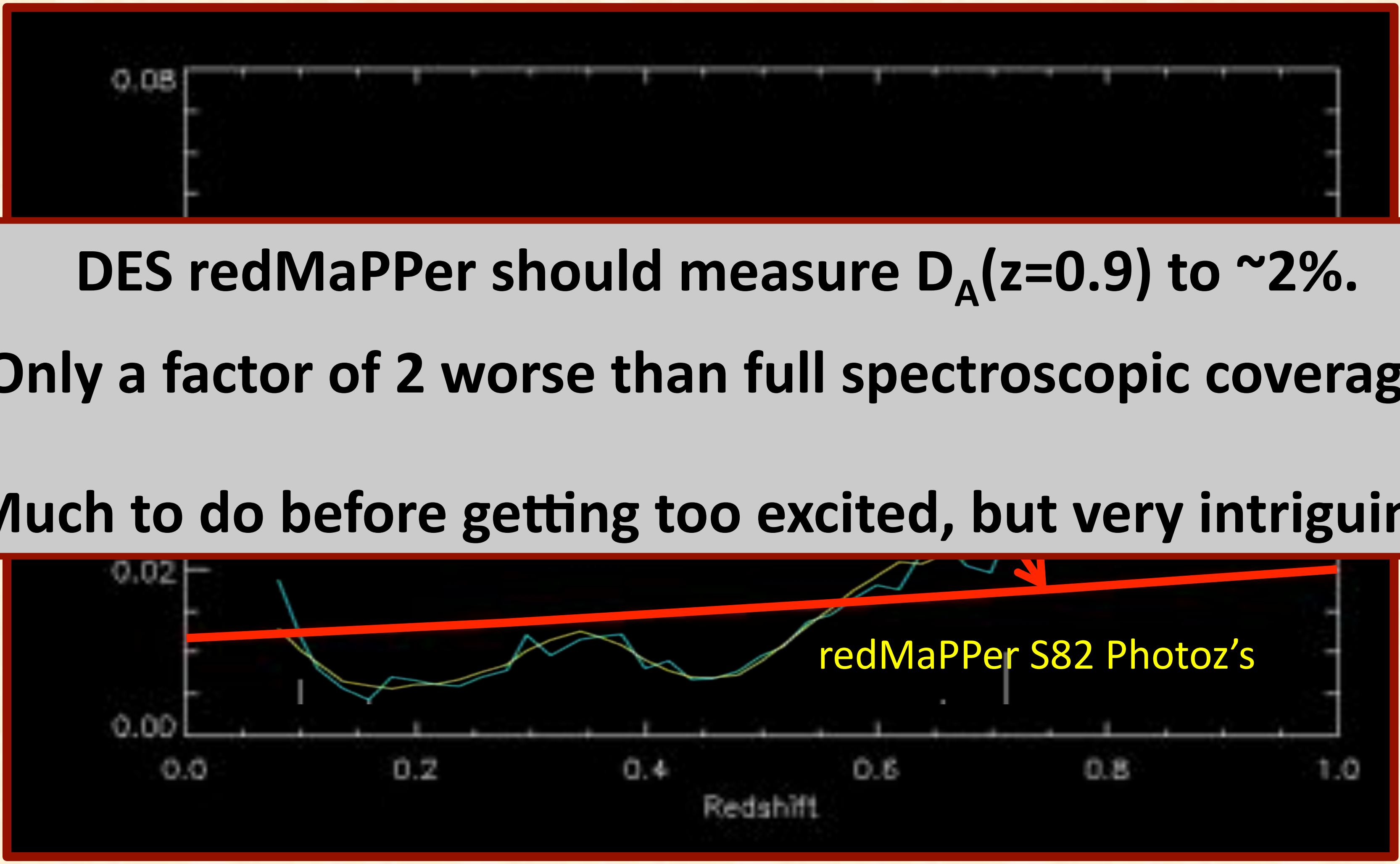
Problem is roughly equivalent to intensity mapping:

redMaPPer objects may not be a single halo, but they are a cylindrical galaxy overdensity.

How Well Can We Do? Forecast Already Published!



How Well Can We Do?
Forecast Already Published!



DES redMaPPer should measure $D_A(z=0.9)$ to ~2%.

Only a factor of 2 worse than full spectroscopic coverage.

Much to do before getting too excited, but very intriguing!

5: The Hiccup

Centering Clusters is Hard!

redMaPPer Approach to Centering

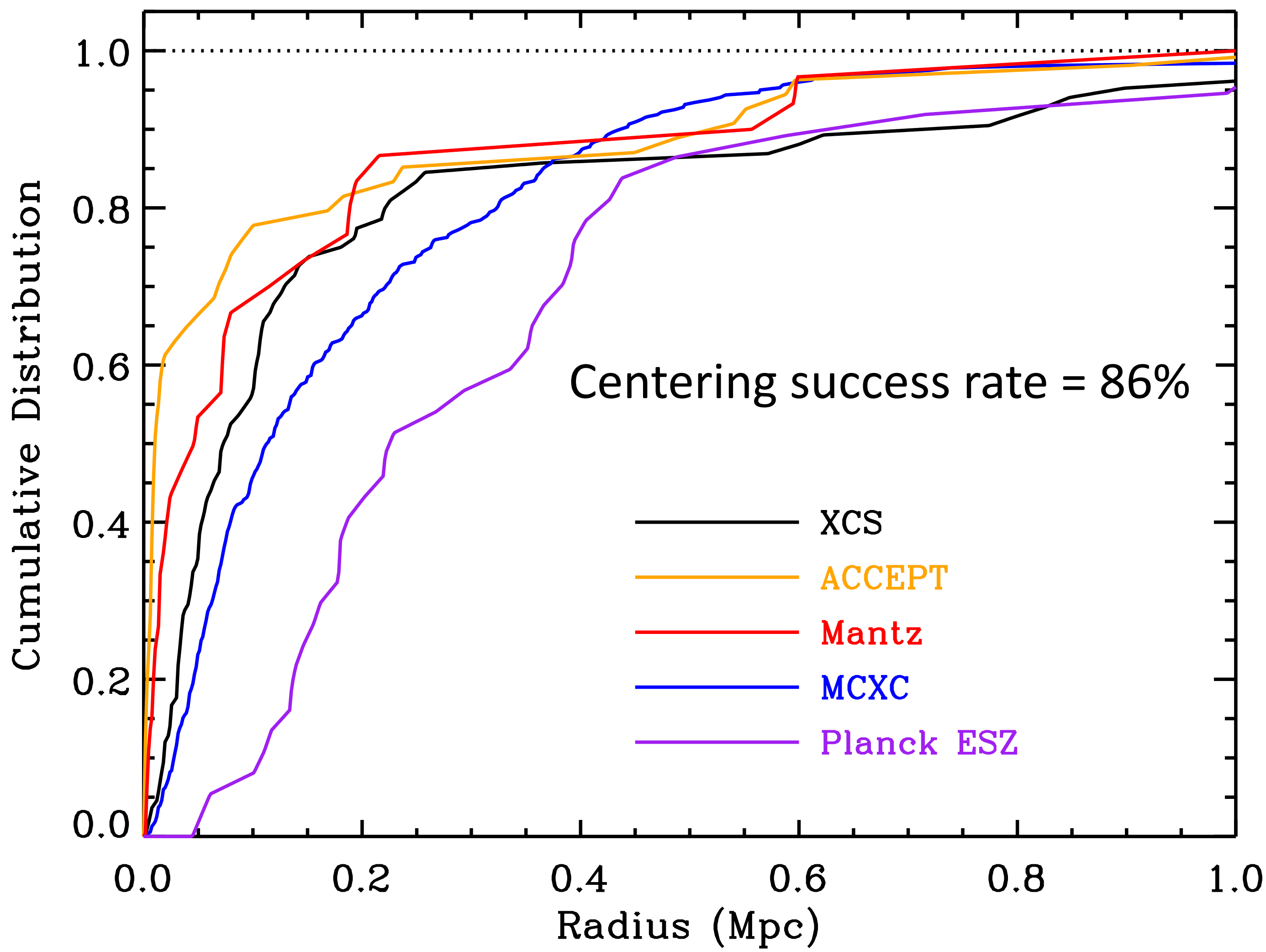
Iterative!

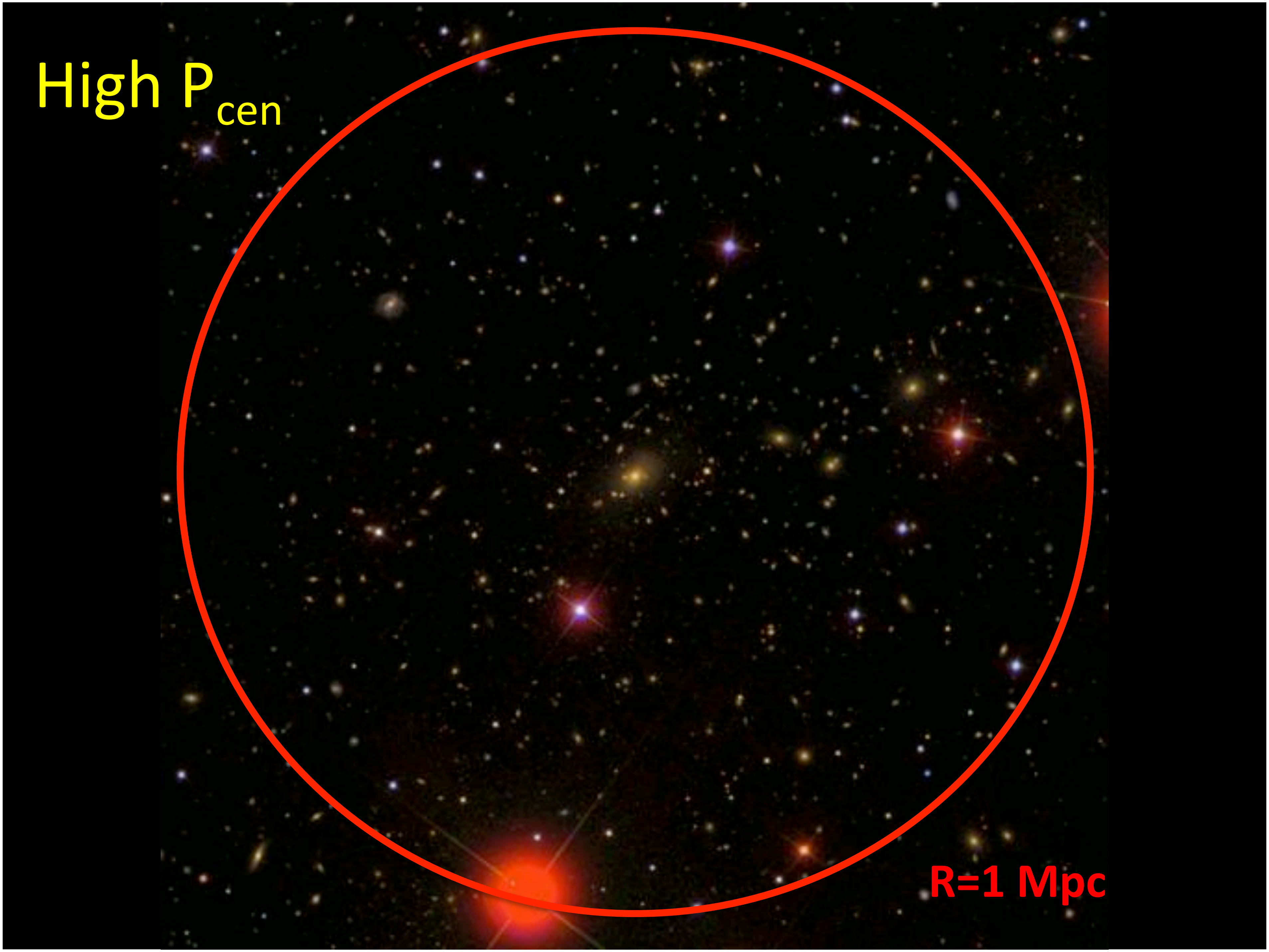
Start with simple guess: center = brightest red-sequence galaxy.

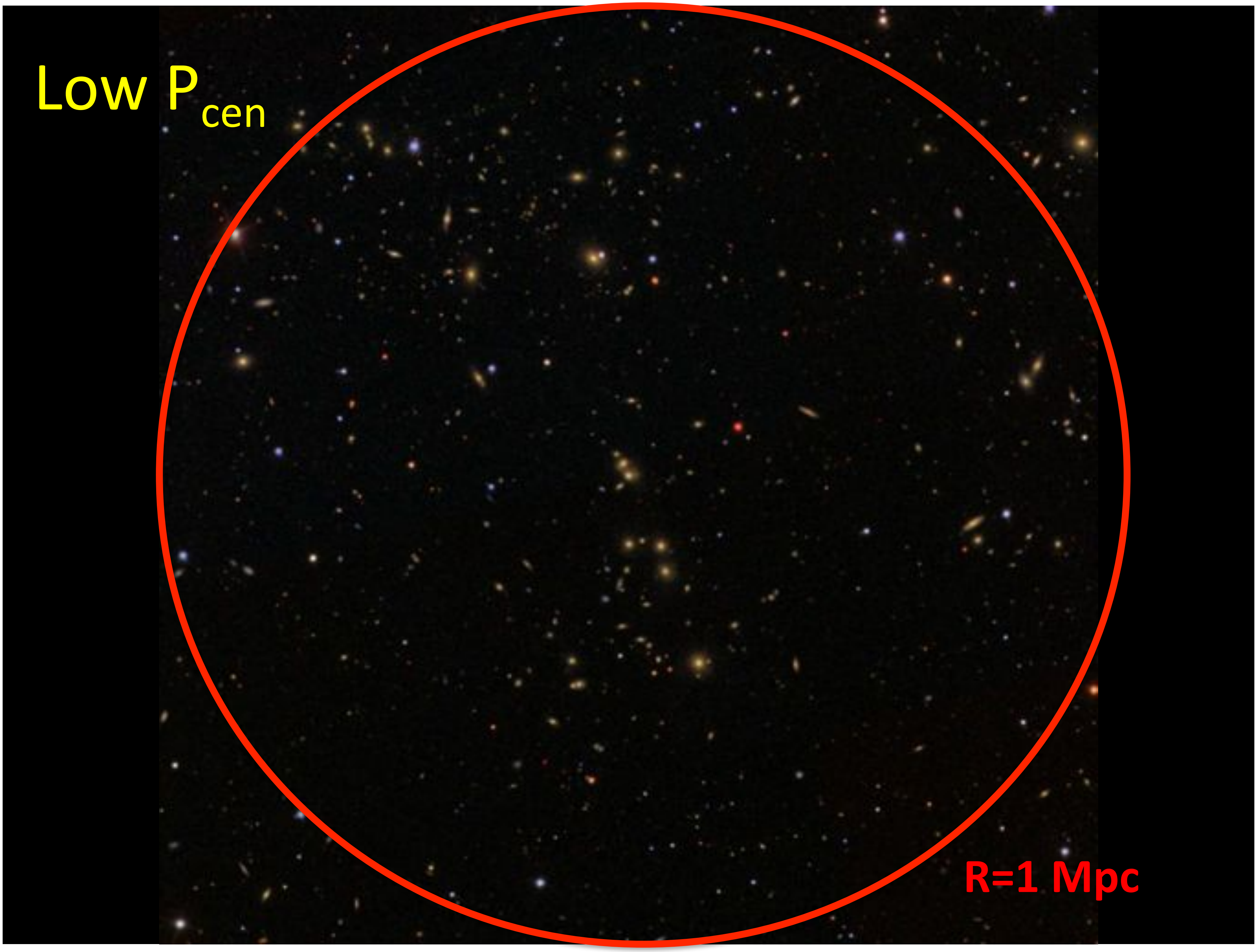
Use initial guess to construct filters for central galaxy properties.

Use filters to relocate centers *and estimate centering probabilities!*

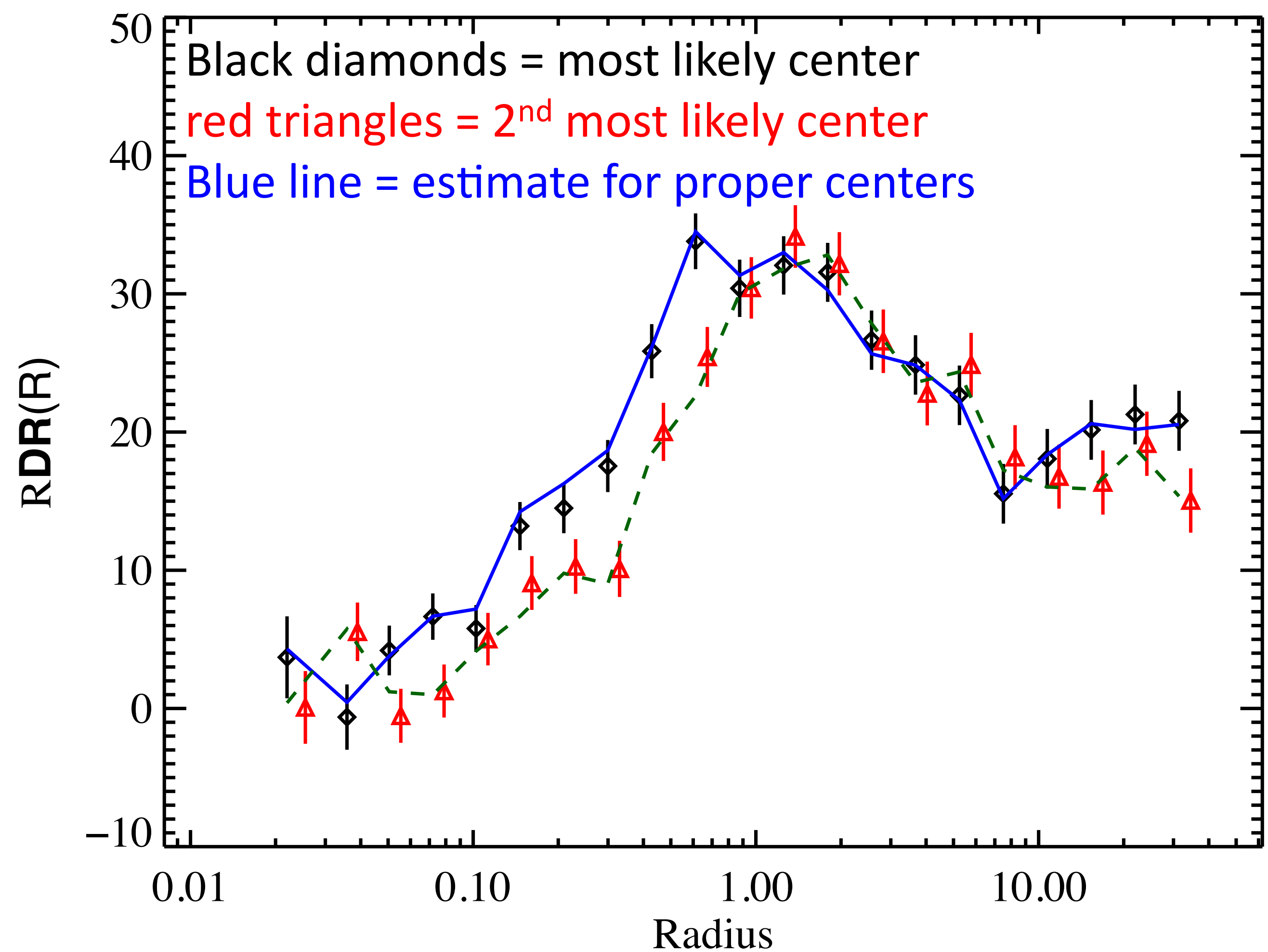
Cluster Centering is Hard




High P_{cen}
R=1 Mpc


Low P_{cen}
R=1 Mpc

Can Use Centering Probabilities to Recover Correct WL Profile



Summary

redMaPPer: Useful Features

- Uses *all* photometric data, not just 1-color.
- Self-training, with minimal spectroscopic requirements.
- Efficient: can run DES in <3 days in 8 cores.
- Generates full P(z) for every cluster.
- Can handle inhomogenous masks.
- Generates its own cluster detection mask.
- Full centering probability for every cluster.

Bottom Line

redMaPPer is demonstrably the best optical catalog to have been run in SDSS.

Completeness/purity and scatter in mass is on par with the best X-ray/SZ catalogs from survey data.

Very accurate, very well understood photoz's.

Appears to be a potentially powerful BAO probe.

Centering still hard, but hope for improvement.

We are developing new statistical techniques to handle miscentering (i.e. probabilitic centers).

Bottom Line: Short Version

Expect current performance will be sufficient to ensure cluster finding systematics to be sub-dominant in DES.

Why Not Use Photoz's Intead?

Partly personal choice: only hand-waivy arguments.

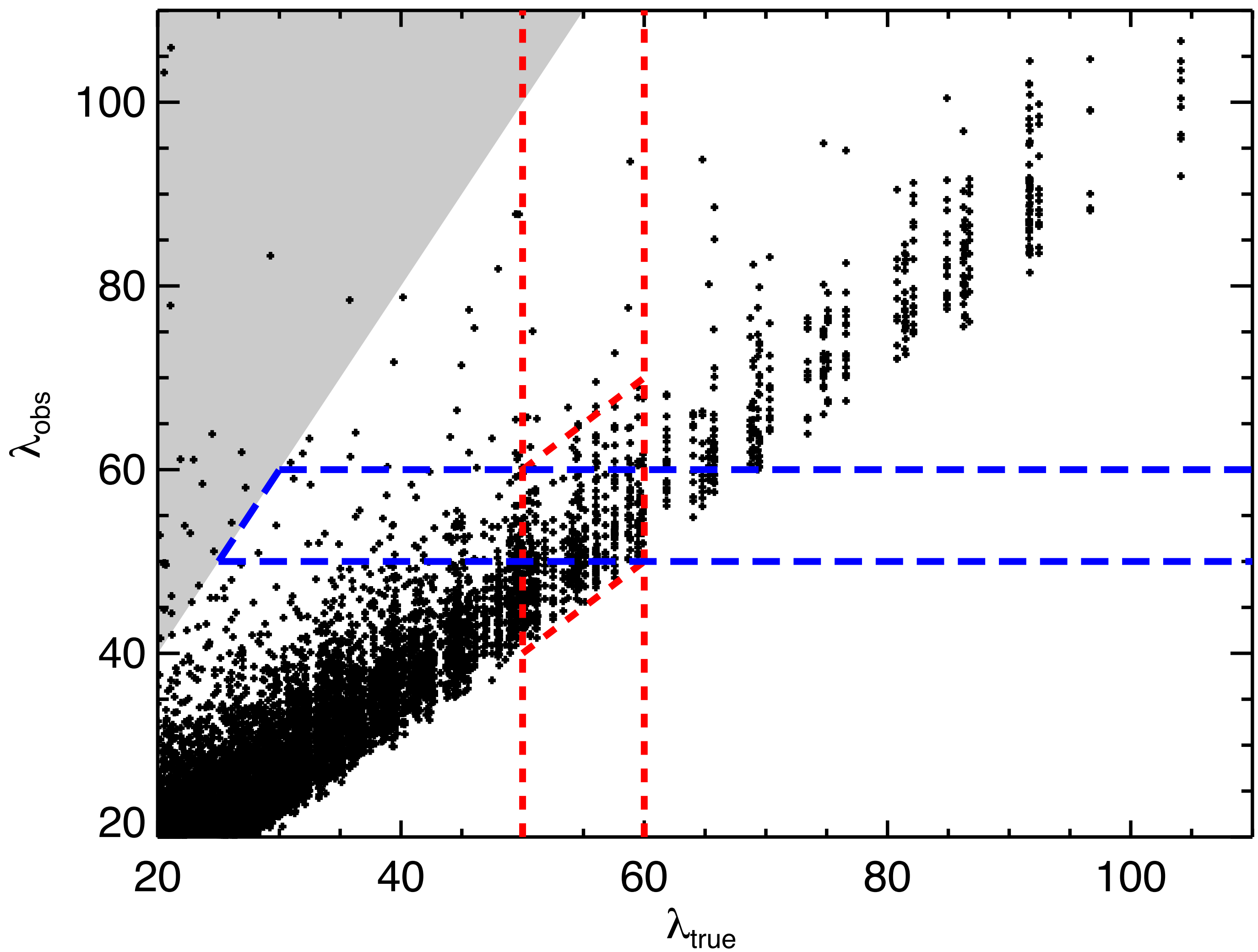
Hand waiving:

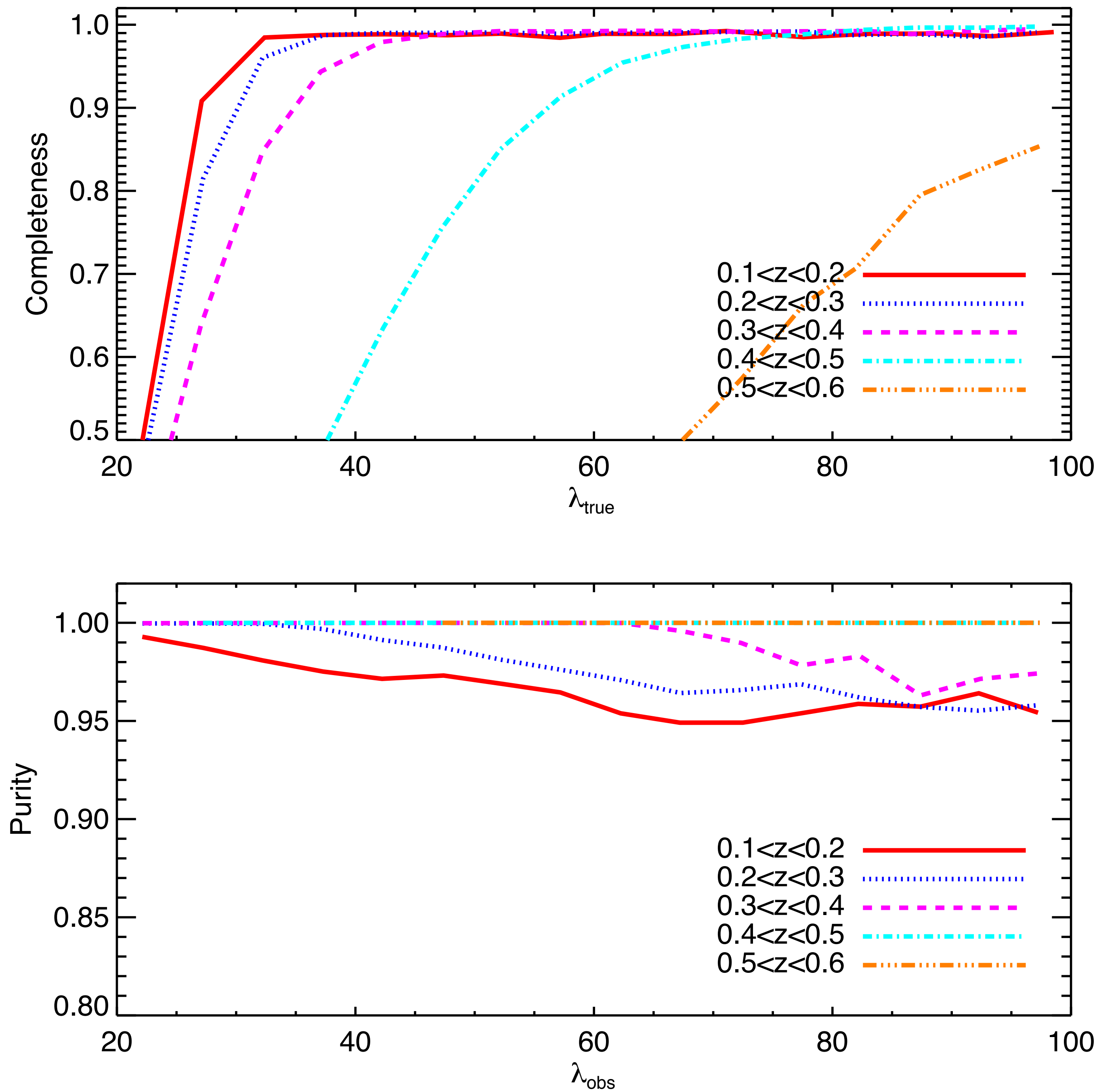
- photoz's are functions of color-data.
- any data massaging can only loose information.

e.g. clustering information can improve photoz's.

- Suggests clustering and photoz's do not commute.

Defining Purity and Completeness

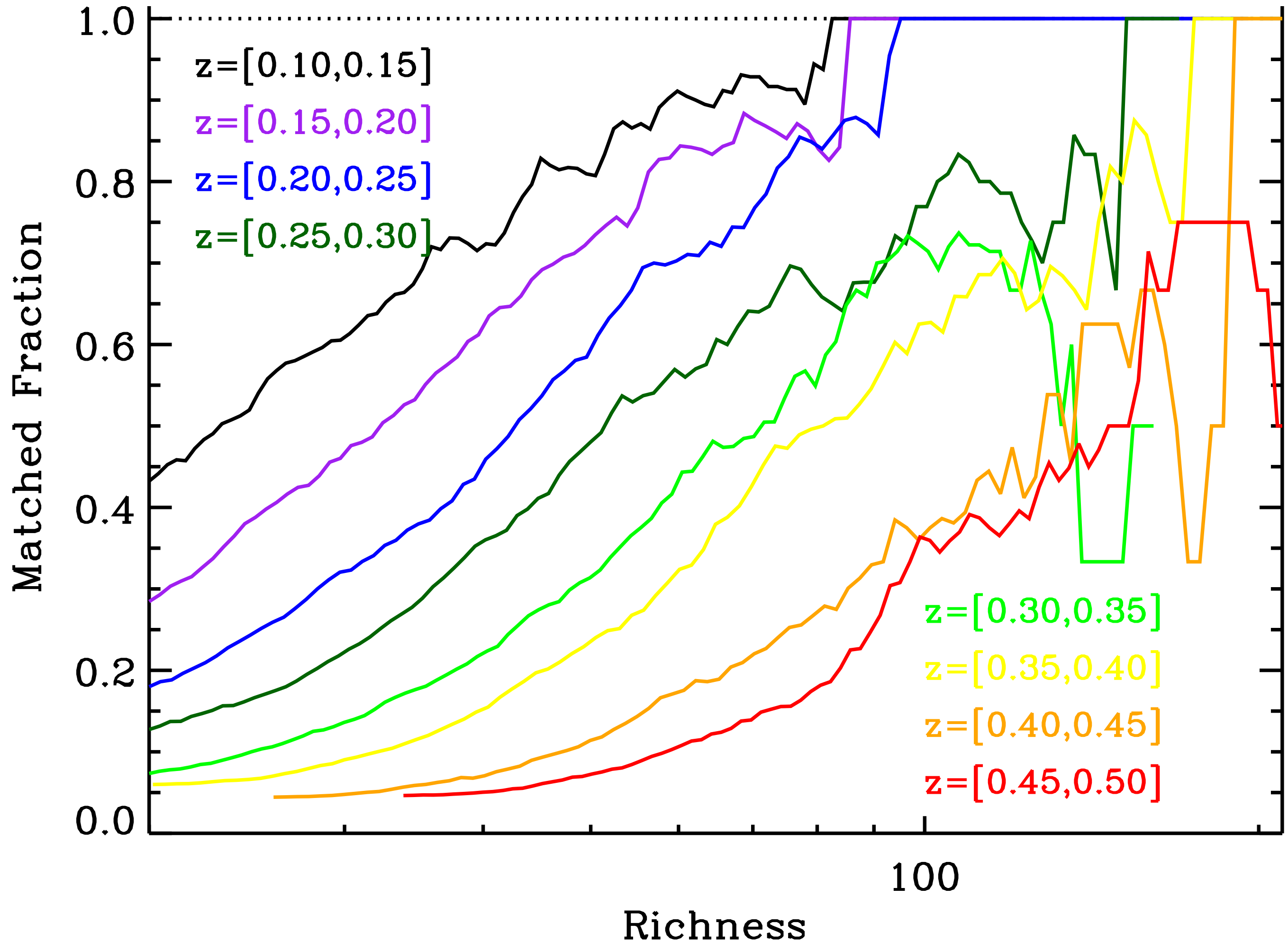




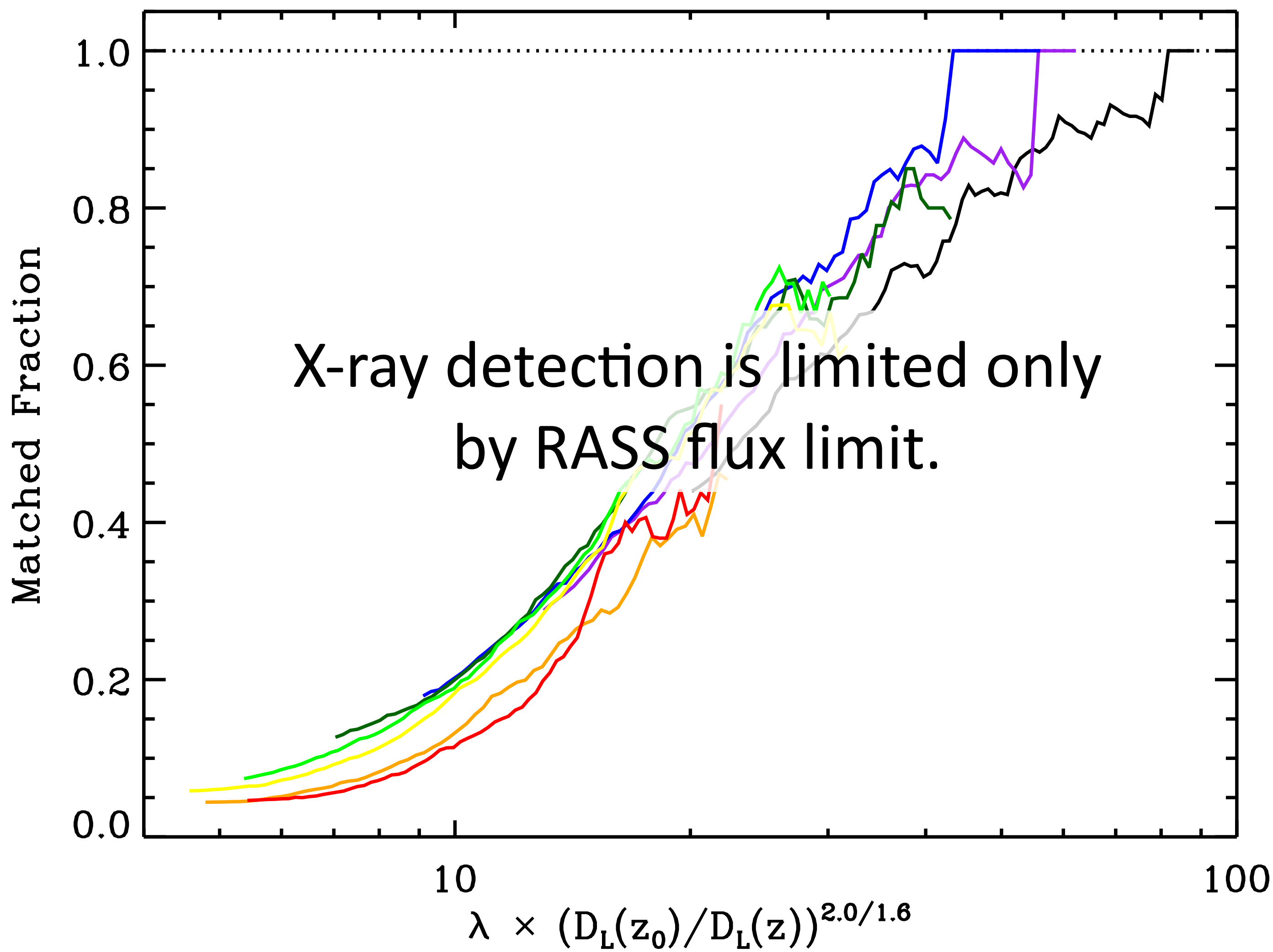
Completeness
1.0
0.9
0.8
0.7
0.6
0.5
20
40
60
80
100
λ_{true}
0.1<z<0.2
0.2<z<0.3
0.3<z<0.4
0.4<z<0.5
0.5<z<0.6
Purity
1.00
0.95
0.90
0.85
0.80
λ_{obs}

X-ray Purity

100% of rich clusters are detected in X-rays



X-ray Purity


X-ray detection is limited only by RASS flux limit.
Matched Fraction
1.0
0.8
0.6
0.4
0.2
0.0
10
100
$\lambda \times (D_L(z_0)/D_L(z))^{2.0/1.6}$